Institut d'Astrophysique de Paris 2007-2011

UMR 7095 CNRS & UPMC

Image cover
Orbiting around
a nearby wormhole /
Alain Riazuelo - IAP

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Institut d'Astrophysique de Paris: an Overview

Description

The Institut d'Astrophysique de Paris (IAP) is a joint laboratory of the UPMC and the CNRS (UMR7095). It has also, internally to the UPMC, the status of an "Observatoire des Sciences de l'Univers (OSU)". With 64 permanent scientists, it is one of the largest laboratories in Astrophysics in France. Research topics cover a large fraction of modern astrophysics. They are grouped in 6 scientific teams:

1- Exo-Planets and Interstellar matter

2 - Stellar and Planetary Physics and Extrasolar Planets

3 - Origin and Evolution of Galaxies

4 - Cosmology and High Energy Astrophysics

5 - Large scale structures and the deep Universe

6 - Theoretical Physics: Gravitation and Cosmology

It should be noted that the Theoretical Physics team is fully integrated within IAP, and is developing collaborations with the astrophysical teams.

The activities at IAP range from observations with large ground based or space telescopes, interpretation and modeling, numerical simulations and theory. IAP is not directly involved in the development of the hardware of instruments for ground based or space observatories. The main goal of IAP as an Institute is to be a place to address the important astrophysical questions by bringing together state-of-the-art results in observations, modeling, numerical simulation results and in theory, in an environment of academic freedom, merging local staff, students and postdocs and a large number of foreign visitors. IAP aims to be an international forum for discussion, confrontation and emergence of new ideas.

In line with a strategic plan defined in the early 2000s, a mid-term plan for IAP had been defined for the period 2008-2011 along 6 priorities:

- To be a center of excellence for extragalactic astrophysics and cosmology
- To be a place for strong collaboration between astrophysics and theoretical physics
- To develop studies in exoplanets and planetary system formation studies
- To make the best use of existing large scale observatories, ground or space based
- To increase the IAP presence in large data processing centers related to IAP scientific priorities, especially for wide field astronomy
- To develop numerical simulations as a common tool

These priorities were the base for the present 5-year term, and will remain so for the next plan.

IAP hosts two major centers for data analysis: 1) the "Planck/HFI Data Processing Center", which coordinates world-wide the analysis of the observations of the Cosmic Microwave Background with the HFI instrument on board of the ESA satellite Planck Surveyor, and 2) TERAPIX for the data processing of wide field imaging, initially the Canada-France-Hawaii Legacy Survey, and now VISTA and the preparation of future Dark Energy observatories, LSST and Euclid. IAP is also involved in the Horizon project, a large project of numerical simulations for cosmology, with the CEA and the Paris and Lyon observatories. In addition, IAP scientists have leading roles in several international projects: Deputy-PI of Planck/HFI, co-PI of Herschel/SPIRE, PI of PLANET (a project to detect exoplanets by micro lensing events) and Exoplanet-SOPHIE, for the detection of exoplanets by radial velocity measurements. This demonstrates the involvement of IAP scientists in leading some of the most prominent projects in Astronomy.

In addition to the research activities, IAP has a strong involvement in the teaching of university-level Astrophysics, Physics and Mathematics at UPMC, with a leading role for the specialized 2nd-year Master's course in Astrophysics for the UPMC. As an OSU, IAP is engaged in several "Services d'Observations" observatory tasks, which, for the IAP, mainly consist in large data centers providing calibrated data to the community. And last but not least, IAP has a strong outreach program, both for the general public and for children in schools.

IAP Activities

Scientific Publications and Highlights

According to a bibliometric study performed by the CNRS/INSU covering the period 2005 – 2007, IAP has been the most productive laboratory in the domain of astrophysics among the French laboratories with 709 papers in total during this period.

The reference list of published papers is given in an Annex document. Note that, during this period, there were 14 papers published in Nature, and 4 in Science including authors from IAP.

The increase of publications between 2004 and 2011 can be correlated with the increased number of post-doc who have been recruited thanks to grants from the Agence Nationale de la Recherche (ANR) and the EU. But this increase is also due to the collaboration of IAP scientists to large international programs: exoplanet detection with HARPS and SOPHIE, the CFHT Legacy Survey, The Sloan Digital Sky Survey and its BOSS extension, COSMOS, the VISTA public Surveys, large programs of high resolution spectroscopy with the VLT, the Herschel large programs KINGFISH, ATLAS, HERMES and HERITAGE, and the Planck project among others. With an average value of 280 papers a year in the last 3 years, the average productivity at IAP is 4.6 papers/year/person.

It is beyond the scope of this summary to review all the results obtained by IAP scientists in the last 5 years. These are described in the activity reports of the teams. Below, we highlight some of them:

- Discovery of the first exoplanet with orbital misalignment and high obliquity (Hébrard et al. 2008). This discovery has deeply modified the paradigm for exoplanet migration; new scenarios are needed to interpret the observations.
- The study of the upper atmosphere of the exoplanet HD209458b in the sodium D lines, and TiO and VO bands revealing the temperature profile (Sing & al, 2008b), and the detection of the evaporation of the atmosphere of the hot Jupiter HD189733b (Lecavelier & al, 2010).
- The statistical analysis of the detection of exoplanets by microlensing indicating that planets in the Milky Way are at least as numerous as stars, and that super-earth and cold Neptunes are 6 times more numerous than hot Jupiter (Cassan & al, 2012)
- The development of large numerical simulations to reproduce the formation of large scale structures and galaxies. These simulations have been used to identify gaseous cool flows for the building of the mass of galaxies compared to large mergers (Dekel & al, 2009). These results have been later confirmed by deep Herschel survey observations.
- The discovery of H_2O emission in lensed sub-mm galaxies identified by Herschel at redshifts larger than 3 (Omont & al, 2011).
- The first detection of CO absorption bands in the line of sight of distant QSOs, implying CMB temperatures at redshift between 1.7 and 2.7 that give a direct proof of the expansion of the Universe (Noterdaeme & al, 2011).
- The first determination of cosmological parameters using weak lensing measurement from the CFHT-Legacy Survey confirming previous independent finding from distant supernovae and CMB analysis (Fu & al, 2008)
- The first set of non cosmological results from Planck ranging from properties of the local ISM to the finding of distant massive cluster using the SZ effect (Planck A&A special issue, 2012)
- For the first time, a second order perturbation theory applied to the Boltzmann equation to compute the propagation of photons and its application to the anisotropy of the CMB generated by the General Relativity (Pitrou & al, 2010).
- The first computation at 3rd Post-Newtonian order ($[v/c]^6$) of the gravitational waves emitted by massive binaries including the spin of the objects (Blanchet & al, 2008, 2011)

Teaching

About 1/3 of IAP scientists have teaching duties, either as professors or associate professors at UPMC (8 persons), or as astronomers (12 persons). Since the creation of the OSU in 2005, all IAP astronomers are affiliated to UPMC, and most of them perform their teaching duties at UPMC. All teaching activities at UPMC are done in the framework of the Physics Department (UFR 925). There are no courses of study associated with the OSU IAP, contrary to many other OSUs in France.

IAP has a leading role for the 2nd-year Master (M2) of Astronomy/Astrophysics program common to the 3 major Ile de France scientific universities (UPMC, Univ. Denis Diderot and Univ. Paris-Sud at Orsay) and to the Paris Observatory. IAP hosts a large fraction of the courses, as well as the M2 secretary office. An IAP Professor is leading the UPMC part of the M2. Some astronomers are also teaching in the 2nd-year Master of Planetology.

IAP is also involved in the Astronomy and Astrophysics doctoral school of Ile de France (ED 127). It is in charge of the scientific and administrative monitoring of all students affiliated to the UPMC. A member of IAP is representing the UPMC at the board of ED 127. IAP scientists (UPMC and CNRS) are contributing to post-Master (doctoral level) classes in domains well represented at the Institute such as on Galaxies, Numerical Simulations or Statistics.

IAP OSU Related Activities: Observatory Tasks

As an "Observatoire des Sciences de l'Univers (OSU)", IAP contributes to Observatory Tasks defined at the national level by CNRS/INSU.

As expected, most of these tasks are linked with data processing, and the development of software tools of general use (SO2 and SO5, following the INSU classification). The main Observation Tasks performed at IAP, among those which benefit from an official recognition by the CNRS/INSU, follow the list of the main large observational projects at the Institute: TERAPIX, Planck DPC, Euclid, ICC Herschel and SOPHIE. These tasks are performed not only by astronomers, but also by CNRS scientists, postdocs and both permanent and temporary software engineers. In total, about 35 FTE persons are contributing to Observation Tasks at IAP, most of them are working on Planck and TERAPIX-Euclid. This represents a significant fraction, more than 25% of the entire IAP manpower, permanent and temporary. This demonstrates that IAP is not a purely academic Institute, but that it plays also a role within the French organization of large observational projects and fulfills its commitments as an OSU.

Some IAP Astronomers are working on Observation Tasks that are not yet recognized as such by the CNRS/INSU. One is the QSO database extracted from the SDSS III-BOSS survey, which should ultimately contain identifications and redshifts for 200 000 QSOs. The other is the development, validation, maintenance, documentation and distribution of a new astronomical software library, AstrOmatic, which contains a dozen tools for image analysis including the widely used SExtractor package. Requests for validation of these two new Observation Tasks have been made to INSU in 2011 and 2012, but the new list of validated tasks is still pending.

A summary table of the Observation Tasks for all IAP astronomers can be found in an Annex document, together with their teaching activities. A detailed description of the activities within each project can be found below (Chapter 7).

Outreach

The staff at IAP devotes a large effort in public outreach. This includes activities towards children at schools (all levels from kindergarten to high school), and activities toward the general public.

A cycle of monthly conferences for the general public has been going on for many years at the Institute. Each month, IAP accommodates 130 persons for a conference mainly on recent astronomical results, but also on other scientific topics such as global warming. These conferences are recorded on DVDs that are sold by CERIMES ("Centre de ressources et d'information sur les multimedias pour l'enseignement supérieur"), and the videos of the conferences are available on the IAP and CERIMES web sites. Since early 2012, these conferences are diffused live by the Canal-U TV channel (http://www.canal-u.tv/). Each year, IAP has a strong involvement in "La Fête de la Science", with open access and activities inside the premises of the Institute, as well as remote participation of scientists. Among other offers, the public has been able to watch live observations, once at the Canada-France-Hawaii telescope in Hawaii, another time at the "Institut de Radioastronomie Millimétrique" (IRAM) in the south-east of France, and this year at the ALMA Observatory. The public can also attend conferences or participate to tutorial demonstrations about the properties of light or data processing. Small children are not forgotten with a dedicated workshop presenting astronomy-oriented games. IAP also a leading role in the organization of an annual astronomy festival in the south of France, le "Festival de Fleurance", welcoming more than a thousand visitors a year.

IAP has been very active in 2009 for the International year of Astronomy, leading 2 major projects: an exhibition of a half-dozen of giant (100 m2!) astronomy pictures displayed during 6 months at the RER B Luxembourg Station, and an astronomy exhibition on the main (Jussieu) campus of UPMC.

Pupils from roughly 30 classes, mainly from neighboring schools, visit IAP every year, while several scientists are guest lecturers in other schools (at all levels from kindergarten to high school). IAP projects in direction of schools are supported by the Ministry of Education program "Sciences à l'Ecole". In this context, an IAP scientist (E. Vangioni) organizes each month a training period (one week) to initiate young pupils to Astrophysics. Another IAP scientist (R. Ferlet) is leading the French participation of the project "EU-Hands on Universe" funded by the European Commission bringing frontline interactive Astronomy to the classroom.

IAP is also associated with several projects with the "Fondation 93", targeted towards the Northen suburbs of Paris. And it has being involved in the ETHER project of the art photographer Gregoire Eloy. This has been the basis for a very large exhibition on IAP walls on boulevard Arago in 2010.

International Recognition

Scientific awards are one of the tools to assess the recognition of IAP scientists. The whole list is on an Annex document. We might just recall here that in the last 5 years, there were among others one bronze medal and one silver medal from CNRS, 5 awards from the French Academy of Science, one price from the Humboldt foundation, the Balzan Prize and three awards from the French Society of Physics, including one for the best PhD thesis in physics.

Many IAP scientists are involved in national and international scientific advisory committees and councils. The entire list of committee membership can be found in an Annex document. We can highlight participation in IAU commissions, the ESA AWG, the HST Time Allocation Committee, the ESO OPC, STC, ELT Working Group and ESO Council (including the President of Council) and for ALMA, ALMA review panels and the ALMA Board (including the Chairman of the Board), the Council of COSPAR, the ASTRONET European Telescope Strategy Review Committee and the Working Group for the Infrastructure Road Map, Directorate of the European journal Astronomy and Astrophysics and in France, CNES «Groupe Astronomie», CPS, ANR selection Panels, CNRS/INSU CSA, National Programs and CNRS/INSU Scientific Council.

Even if IAP is not involved directly in instrument design and manufacturing, several scientists have a leading role in large international projects: F. Bouchet is Deputy PI of Planck/HFI, L. Vigroux is co-PI of Herschel/SPIRE, Y. Mellier is the Euclid Consortium Lead, J.-P. Beaulieu is the French co-PI of the ECHO proposal selected for the next M3 ESA mission studies. They are also involved in the scientific teams of many international space or ground-based projects at various levels: JWST/NIRSPEC, Herschel and Planck Science teams, Euclid Consortium, and Virgo. And they are leading or participating in many large (or key) programs on ESO and ESA observatories like KINGFISH, HERITAGE and ATLAS on Herschel, BOSS on the Sloan Telescope, ULTRA-VISTA and VIKING on ESO/VISTA and the CFHT-LS and COSMOS-U at CFHT. Moreover, J.-P. Maillard has collaborated to the design of one of the three instruments planned for CFHT in 2013, the SITELLE (a UV-VIS-NIR wide-field imaging Fourier transform spectrometer optimized for astronomical observations of extended objects).

As an Institute, IAP benefits from a wide international audience and is able to attract many top-level foreign scientists. In the last few years, two high-visibility senior foreign scientists have joined IAP, one through recruitment at CNRS (M. Volonteri), the other by internal mobility (M. Lehnert). A prominent astronomy professor, J. Silk, has chosen IAP for his ERC-funded project on Dark Matter. In 2008, the UPMC has opened an international chair of theoretical cosmology at IAP. We received 22 applications for this position, and the position was filled by Prof. Benjamin Wandelt from the University of Illinois, who later won an ANR Chaire d'Excellence. J. Silk and B. Wandelt have pooled their resources, creating the Initiative de Cosmology à Paris (ICAP). More than 200 candidates have applied to the first ICAP call for postdocs. At the 2012 CNRS hiring competitive process, there were 26 applicants, 14 of them being foreigners. In 2010, there were 29 candidates for a position of associate professor open by UMPC at IAP, including 2/3 of candidates without existing links with the Institute. IAP is sustaining a strong visitor program on its own funds. Typically, we host 80 to 100 visitors a year, for periods ranging from a few days to several months.

The annual IAP Colloquium participates to the visibility of the Institute. Every year, in late June or early July, IAP organizes a topical meeting attended by roughly 120 scientists. The full list of these colloquia can be found on the IAP website. Topics change every year and span a wide range of astrophysical problems. For example, the last 3 colloquia were entitled: *Progenitors and Environments of Stellar Explosions, From Dust to Galaxies, and Stellar Population across Cosmic Time*. This last meeting was organized in partnership with the Subaru Telescope and the Japanese NAOJ. During each of these colloquia, an IAP medal is granted to one exceptional scientist within the field of the meeting. The last medalists were Profs. R. Blandford, C. Steidel, W. Sargent, K. Nomoto and N. Arimoto. In addition to this annual colloquium, IAP hosts 2 to 3 more topical workshops a year.

The weekly Friday seminar, organized by R. Mohayaee, is another institution contributing to the scientific life and the visibility of the Institute. The talks given by high-level astrophysicists or physicists, most of them foreigners, are very popular with an average attendance of 50 people with some peaks above 100. The list of past seminars can be found on the IAP website and in an Annex document.

Due to its central position in the Paris metropolitan area, to the availability of its auditorium and several meeting rooms, as well as to the open rooms policy of the Institute, IAP is in high demand to host an important fraction of administrative and scientific meetings in France for the CNRS in general, but also for project consortium meeting, scientific committees or topical meetings of the INSU National Programs. There is probably not a single active French astronomer who did not attend at least one such meeting at the IAP during the last 5 years.

These facts explain the high reputation of IAP abroad and in France, and contribute to make our Institute a very exciting place to work, with always something new taking place.

IAP in the National Context

IAP was created in 1938 by the "Caisse Nationale de la Recherche Scientifique" (that became the present day CNRS the year after) to be the place for the development of modern Astrophysics. Ever since, this remains the main goal of IAP's direction and staff. Until 2000, IAP was a laboratory fully attached to CNRS, one of the two, so called "Laboratoire Propre du CNRS", among Astronomy laboratories in France. As such, it had always benefited from a strong support by CNRS. In particular, all the infrastructure costs are always paid by CNRS, which owns the building. In 2000, IAP became a joint unit (Unité Mixte de Recherche) between the CNRS and UPMC following the general trend of increased collaboration between CNRS and the universities. Later, in 2005, IAP became an Observatoire des Sciences de l'Univers (OSU) of the UPMC. This was recognition for the implication of IAP staff in teaching at UPMC, and its contribution to observational duties, in particular with Planck DPC and TERAPIX. As an OSU, IAP is one of the 14 UPMC "components", which provides us with higher visibility than a standard UMR. Moreover, since OSUs are created by ministerial decree, IAP benefits from a longer-term stability in comparison to standard UMRs, which are renewed every 4-5 years. This history and recent evolution have ensured IAP with a very visible position, both within CNRS and UPMC.

The staff from IAP is strongly involved in the administration of French Astronomy and Astrophysics. Scientists from IAP are chairing or have chaired the INSU "Conseil Scientifique", and the "Programme National de Cosmologie et des Galaxies" (PNCG) and they contribute to most of the CNRS advisory committees in the domain of Astrophysics. They are members of the CNES "Comité des Programmes Scientifiques", and of the Astronomy Working Group. They contribute to the ANR project selection panels. The full membership list of IAP scientists is contained in the Annex document.

IAP scientists have been successfully taking advantage of the new funding opportunities offered in the French science system: from ANR, as well as the Initiatives d'Excellence, and the Region Ile de France. Since the creation of the ANR in 2005, IAP scientists have contributed to 12 and chaired 4 ANR white projects for a total budget of 1.940 M€, and chaired 4 Young Scientist grants for a total of 0.6 M€. In addition, B. Wandelt has obtained an ANR "Chaire d'Excellence".

In the framework of the Initiatives d'Excellence (IDEX), IAP was at the origin of a "Laboratoire d'Excellence" (LABEX) proposal, Institut Lagrange de Paris (ILP), in association with the LPNHE and the LPTHE at UPMC, the Institut Henri Poincaré, the Collège de France, and a team from the Paris Observatory. The aim of this LABEX is to develop research activities and training of young scientists in the domain of theoretical and observational cosmology, with an emphasis on dark matter and dark energy. This proposal was accepted in the first call, and was ranked among the 39 equally best proposals (Grade A+) among all science projects throughout France. The ILP is now part of the IDEX "Sorbonne – Universités". It will contribute to the international visibility of IAP through the visitors, PhD and postdoc programs that are the largest expenses of the LABEX. In the domain of exoplanets, IAP is associated to the LABEX ESEP (Exploration Spatiale des Environnements Planétaires) under the leadership of the Paris Observatory.

IAP is one of the funding laboratories of the Research and Formation proposal "Astrophysique et Conditions d'Apparition de la Vie" (ACAV) to the region Ile de France. This proposal was accepted as one of the 16 "Domaines d'Intérêt Majeur" (DIM) of the Région Ile de France. The IAP director is a member of the steering committee of this program, and scientists from IAP contribute to the Scientific Committee of the DIM.

Being active, and even better successful, in finding new funding resources has proved to be vital for the future of IAP, in a context where the traditional funding by CNRS and the University has continuously decreased over the last 5 years. In total, research contracts represent now about 75% of our budget if we do not include the CNRS and UPMC labor costs.

These facts demonstrate the prominent role of IAP in the national context of the French Astronomy.

Extrasolar Planets and Interstellar Media

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The research team “Extrasolar Planets and Interstellar Media” consists of:

3 CNRS researchers: Roger Ferlet, Guillaume Hébrard, Alain Lecavelier

1 CNRS researcher emeritus: Alfred Vidal-Madjar

1 astronomer: François Bouchy

1 research engineer: Jean-Michel Désert (until 2010)

From 2007 to 2011:

2 postdocs: Rodrigo Díaz, David Sing

3 PhD students: Isabelle Boisse, David Ehrenreich, Benoît Loeillet

4 theses were defended: Isabelle Boisse, Jean-Michel Désert, David Ehrenreich, Benoît Loeillet

2 “habilitations à diriger les recherches” were also defended: François Bouchy, Alain Lecavelier

3 prizes were awarded by the Academy of Sciences and CNRS: François Bouchy (bronze medal), Alain Lecavelier (Price Del Ducca), Alfred Vidal-Madjar (Price Ampère)

HDR: 4

Publications: I: 178 – II: 90

The team "Extrasolar Planets and Interstellar Media" is a result of a reorganization of the scientific teams of IAP in 2008. Its unifying theme is the detection and characterization of extrasolar planetary systems.

The team has unique expertise in the radial velocity method, the main method for discovering extrasolar planets, as well as in transit spectroscopy, a particularly powerful method for detecting and characterizing the atmospheres of exoplanets. The team also has recognized competence in modeling the atmospheres of exoplanets.

For a long time, the team members were heavily involved in the FUSE space mission of UV spectroscopy through studies of the interstellar medium but also of young circumstellar disks and planets of the solar system. FUSE was terminated by NASA in July 2007. The contribution of IAP in terms of refereed published articles related to FUSE has therefore decreased until the very end of the financial contribution of CNES in 2010.

Since the late 1980s, several team members have been involved in the EROS project. We used the microlensing effect to search for baryonic dark matter in the form of compact objects in the halo of our Galaxy. A definitive result of this project was to exclude the presence of compact objects in the range $0.6 \times 10^{-7} - 15$ Msol in the Halo (Tisserand et al. 2007). As a matter of fact, the seven years of EROS observation have resulted in the creation of an impressive database of light curves (for about 100 million objects, including 35 million in the Magellanic Clouds). The EROS group of IAP decided to exploit it in terms of variable objects. Two team members are still associated with publications signed by the whole EROS consortium.

Finally, several team members are very active in the dissemination of scientific knowledge. In particular, one member is co-director of the worldwide project Global-HOU (Hands-On Universe) and co-coordinator of its European part EU-HOU (partly funded by European contracts). This project aims to implement inquiry-based methods in secondary science education in the context of astronomy.

1.1 Radial Velocimetry

1.1.1 Search for and Discoveries of Extrasolar Planets

The first planet orbiting a solar type star was discovered in 1995 at the Observatoire de Haute-Provence (OHP) with the ELODIE spectrograph. Since then, exoplanetology has developed significantly: nearly 700 extrasolar planets have been discovered, primarily through the radial velocity method, which allows the indirect detection of a planet thanks to the very precise measurements of motions it induces on its parent star. Less and less massive exoplanets are now within reach – hopefully down to Earth mass, with longer and longer periods. Our team is actively involved in these programs, in particular through a Young Researcher grant awarded by the French National Research Agency (ANR), entitled "Super-Earths" and led by F. Bouchy.

The SOPHIE spectrograph was commissioned in 2006 at the 193 cm telescope of the OHP. This echelle spectrograph is fed by optical fibers and housed in a stabilized environment. It is one of the most accurate instruments in the world for radial velocity measurements. A consortium of about twenty European researchers receives on average more than one hundred observing nights with SOPHIE per year. It is therefore able to conduct an ambitious and competitive program, organized into five sub-programs: 1) high accuracy search for low mass planets, 2) detection and study of giant planets, 3) search for planets around M dwarfs, 4) search for planets around early stars, and finally 5) search for planets with long periods using the ELODIE data (some dating back to 1994). This consortium is led by F. Bouchy and includes G. Hébrard (responsible for one of the sub-programs), A. Vidal-Madjar (until 2010), R. Diaz (postdoc since 2009), I. Boisse (thesis defended in 2010); A. Lecavelier is also collaborating in some of the sub-programs.

Many new planets and brown dwarfs have already been detected and reported (Da Silva et al. 2007, Santos et al. 2008, Bouchy et al. 2009, Desort et al. 2009, Hébrard et al. 2010a, Boisse et al. 2010, 2011 , Diaz et al. 2011); more discoveries are in the process of being published. A study of the activity of the star HD189733, host of one of the most famous transiting planets, has also been possible thanks to a SOPHIE campaign (Boisse et al. 2008). Group members also detected the absorption spectrum of the Earth during a lunar eclipse, which reproduces an exoplanetary transit (Vidal-Madjar et al. 2010).

1.1.2 Obliquity and Orbital Characteristics

Many transiting exoplanets have also been observed with SOPHIE, allowing the measurement of the obliquity of these systems (Loeillet et al. 2008, Moutou, Diaz et al. 2011). Thus, our observations of the planet XO-3b enabled us to publish the first case of non-alignment between the stellar rotation axis and the revolution axis of the planet (Hébrard et al. 2008; Figure 1.1). This result was confirmed by Keck observations.

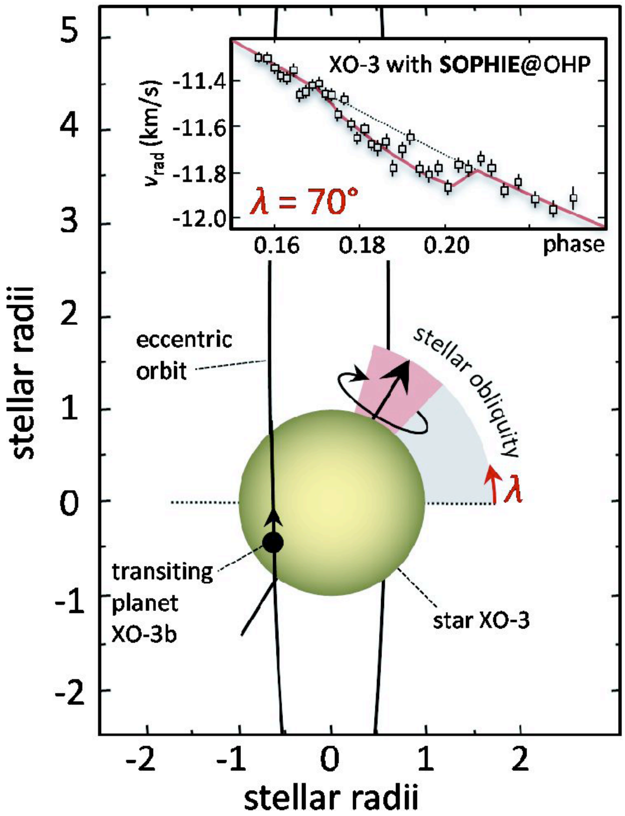


Figure 1.1. *Spectroscopic transit of the exoplanet XO-3b observed with SOPHIE. This has led to the detection of the first known case of non-alignment between the stellar rotation axis and the revolution axis of the planet.*

We have also published the detection of the spectroscopic transit of the planet HD 80606b, together with its photometric detection which was simultaneously done at the 120 cm OHP telescope (Moutou, Hébrard et al 2009). It was then the longest orbit for a transiting planet (111 days period, the previous record was 21 days). Our SOPHIE observations indicated a non-alignment rotation-orbit, second case after XO-3b. We confirmed this non-alignment by combining all the data then available (Pont, Hébrard et al. 2009), and performed a simultaneous campaign with SOPHIE and the Spitzer Space Telescope to specify the parameters of this system (Hébrard, Désert , Diaz et al. 2010b).

Following the first two cases of rotation-orbit non-alignments from the SOPHIE consortium, others were observed, including retrograde orbits (e.g. Winn et al. 2009, Triaud et al. 2010, Queloz et al. 2010, Hébrard et al. 2011). Taken together, these results call into question migration in the disk as the standard, unique model able to explain the origin of giant planets close to their star; they have led to numerous theoretical works.

1.1.3 Observation of Planet Candidates Detected by Transit

We also participate in a second major program of SOPHIE, which aims at tracking radial velocities of planet candidates detected in transit by ground- and space-based photometric surveys. This is a compulsory step for establishing the planetary nature of the transits, and subsequently for characterizing the detected planets, in particular measuring their mass and the eccentricity of their orbits. This SOPHIE program uses on average 80 nights per year. It has produced many results, including the detection and characterization of twenty SuperWASP planets (e.g. Cameron, Bouchy, Hébrard et al. 2007, Bouchy et al. 2010, Simpson, Pollacco, Hébrard et al. 2011, Hébrard et al. 2012) and two HAT planets. SOPHIE is also one of the two pillars, with HARPS, for the radial velocity follow-up of the CoRoT space mission and has contributed to the detection and characterization of over 20 CoRoT planets (e.g. Moutou, Pont, Bouchy et al . 2009, Fridlund, Hébrard et al. 2010, Bordé, Bouchy, et al. 2010, Bouchy et al. 2011, Hébrard et al. 2011, Guenther, Diaz et al. 2011). Finally, in 2010, we began a campaign of follow-up observations of the extrasolar planet candidates from the U.S. Kepler space mission (Ehrenreich, Lagrange, Bouchy et al. 2010, Santerne, Diaz, Bouchy et al. 2011, Bouchy et al. 2011, Santerne, Bonomo, and Hébrard al. 2011, Bonomo, Hébrard et al. 2011, Diaz et al. 2012). The experience gained from these programs will be reinvested in future programs aiming at the detection and study of transiting planets, including the TESS mission pre-selected by NASA, with which we are associated.

1.1.4 National and International Collaborations

The major involvement of our team in the programs carried out with SOPHIE led three of us (F. Bouchy, G. Hébrard, R. Diaz) to conduct long-term missions at OHP. Thus, we are able to monitor the instrument and the observations closely, and, in particular, participate in technical improvements to SOPHIE actively. For example, a portion of fibers with an octagonal section was introduced in the fiber pipeline in June 2011, bringing a very significant gain in radial velocity accuracies, now of the order of 1 m/s. SOPHIE is the first instrument to be equipped with such a system, which is currently being studied for other spectrographs. These long-term missions have also helped to strengthen and develop collaborations between teams from IAP and OAMP working on exoplanets.

We also participate in programs of radial velocimetry conducted in the Southern Hemisphere with the HARPS spectrograph, installed at the focus of the ESO 3.60 m telescope at La Silla. F. Bouchy leads an ESO large program to follow the CoRoT mission (Bouchy et al. 2008, Queloz, Bouchy et al. 2010, Gandolfi, Hébrard et al. 2010), in synergy with SOPHIE, and we are associated with several programs in radial velocity surveys (e.g. Bouchy et al. 2009, Triaud, Queloz, Bouchy et al. 2009, Hébrard et al. 2010c). Finally, we participate in the development of the SPIRou high precision spectrograph, which is to be installed at the focus of the CFHT in order to achieve radial velocimetry in the infrared focusing on M dwarfs. These stars make up the majority of stars in the Galaxy; having small radii and masses, they ease the detection of small planets (in transit or not) with low temperatures, thus facilitating the detection of planets in the habitable zone.

1.2 Spectroscopy of Transits

Another approach to detect extrasolar planets is to measure the periodically tiny drop in brightness of a star due to the passage of a planet in front of its disc (photometric transit). This is an optimal configuration for detailed spectrophotometric studies, enabling us to observe and characterize the atmospheres of extrasolar planets.

1.2.1 Discovery of the Evaporation of Hot Jupiters

Our team observed HD209458b with the Hubble Space Telescope (HST) in search of atomic hydrogen with the UV Lyman-alpha line, which led to the discovery of the evaporation of this planet (Vidal-Madjar et al. 2003). With an escape rate of 1010 g/s, the hydrogen cloud covers 15% of the surface of the star, much larger than the Roche lobe, and the atoms are observed at a speed of more than 100 km/s, exceeding the escape velocity (Lecavelier des Etangs et al. 2004). All the analyses now converge: HD209458b is evaporating (Vidal-Madjar et al. 2008; Ehrenreich et al. 2008, Linsky et al. 2010).

We also found the presence of carbon and oxygen in the upper atmosphere of this planet (Vidal-Madjar et al. 2004), which demonstrates the hydrodynamic regime of the evaporation, similarly to what has probably eliminated the primitive atmosphere of the Earth. This has been confirmed with the new spectrograph COS of HST (Linsky et al. 2010).

Observations of another transiting planet in front of a bright star – HD 189733b – were programmed with the STIS spectrograph of HST, but were delayed due to its failure. Meanwhile, we search for signatures of evaporation of HD189733b by using the HST prism spectrograph ACS. The hydrogen cloud has been detected and the planet also evaporates with an escape rate of 10^7 - 10^{10} g/s. This is the second case of evaporation of an extrasolar planet (Figure 1.2; Lecavelier des Etangs et al. 2010).

The origin of hydrogen atoms in hot-Jupiters exospheres is still debated. There are two scenarios: formation by recombination of the stellar wind protons with the electrons in the atmosphere, or direct origin from the atmosphere and acceleration by radiation pressure (Holmström et al. 2008; Lecavelier des Etangs et al. 2008c). As a matter of fact, in both cases the planet evaporates (Lecavelier des Etangs et al. 2008c).

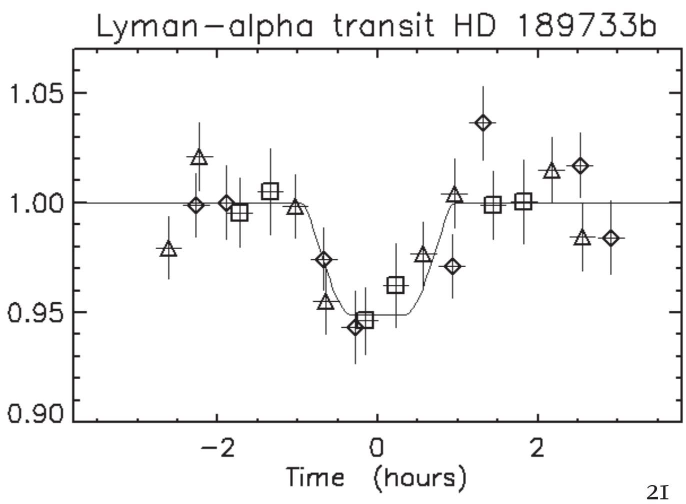


Figure 1.2. *Lyman-alpha flux vs. time for the transit of HD189733b observed with HST (Lecavelier et al. 2010). Detection of the hydrogen escape, which produces 5% absorption during the transit (corresponding to the 15% measured with the other HST spectrograph when its higher resolution is taken into account).*

All these results have led to a large number of theoretical developments concerning the mechanisms involved in the evaporation of hot Jupiters. All the models show that nearly 100% of the energy input in the form of stellar X-ray and extreme ultraviolet are used to escape the potential well of the planet. This has been the general basis for the development of "energy diagrams" described in Lecavelier des Etangs (2007) that predict the rate of evaporation of extrasolar planets and determine their evolution. They also explain the lack of low-mass giant planets close to their stars and predict the existence of planets in the form of evaporation residues (Lecavelier des Etangs 2007), as observed in the case of the planet Corot-7b (Léger et al. 2009).

1.2.2 Detection and Characterization of Exoplanet Atmospheres

The detailed study of the atmospheric structure of exoplanets can be achieved through spectroscopic observations of transits with the Space Telescopes Hubble (in the visible) and Spitzer (in the IR) (Tinetti et al. 2007a). The analysis and interpretation of observations of HD189733b at 3.6 and 5.8 microns at first led to the announcement of the detection of water molecules (Tinetti et al. 2007b), but this detection has since been challenged by a new detailed analysis of the same data (Ehrenreich et al. 2007; Désert et al. 2009). Later, a new set of Spitzer data yielded an overall measure of the absorption spectrum from 3 to 8 microns and led to the detection of high CO/H^2O in the atmosphere of HD189733b (Désert et al. 2009).

Using the HST measurements, we have also shown that the spectrum of the atmosphere of HD189733b between 0.55 and 1.05 microns is characteristic of Rayleigh scattering. It was also possible to measure the temperature of the atmosphere ($T = 1340 \pm 150$ K). Particles responsible for the Rayleigh scattering could be aerosols composed of $MgSiO^3$ such as those predicted to be abundant in this type of atmosphere (Fortney et al. 2007; Lecavelier des Etangs 2008a).

Finally, we have initiated a systematic analysis of all the HST data from HD209458b to produce an absorption spectrum by its atmosphere from 3000 Å to 8000 Å (Figure 1.3, Sing, Vidal-Madjar et al. 2008a). Thanks to this spectrum, many discoveries have been made, such as:

a. The detection of the Rayleigh scattering by hydrogen molecules (Lecavelier des Etangs et al. 2008b); this measurement enables us to set the unknown pressure-altitude relation necessary to convert the detection of other elements in terms of absolute abundance.

b. The detection of different atmospheric layers with different abundances of sodium as a function of altitude (Sing et al. 2008b). This is the first observation of an abundance variation in the atmosphere of an extrasolar planet.

c. The detection of TiO and VO molecules predicted by theoretical models and whose presence is necessary to interpret the excess absorption we observe between 6500 Å and 7500 Å (Désert et al. 2008).

d. The measurement of the temperature-pressure profile from ~100 millibars to 10 microbars, with an adiabatic profile from 2200 K to less than 700 K (Sing et al. 2008b, Vidal-Madjar et al. 2011).

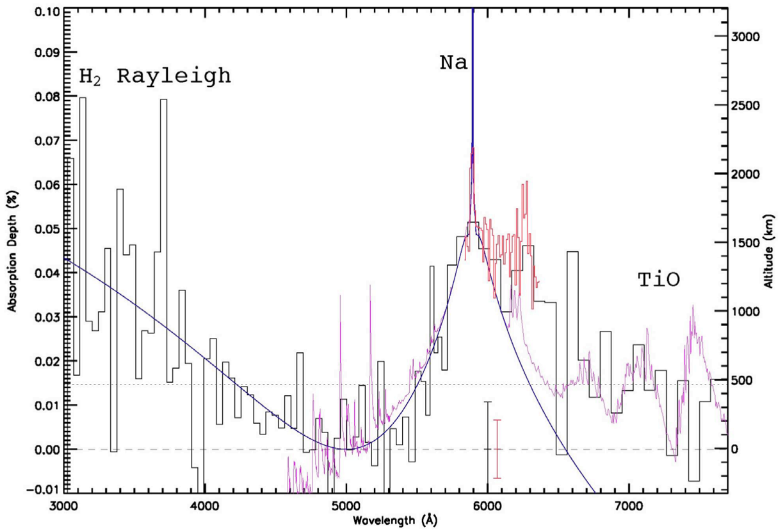
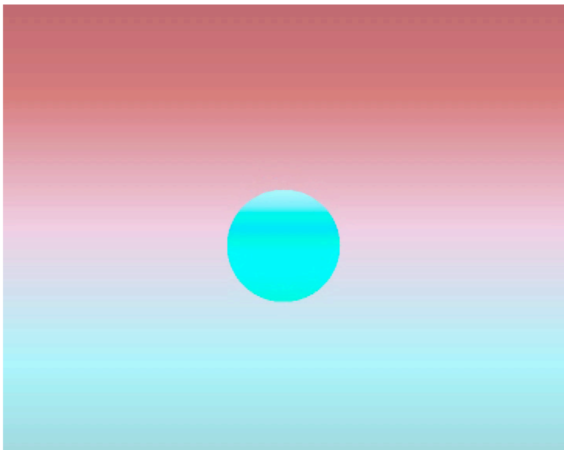


__Figure 1.3.__ Absorption spectrum of the atmosphere of HD209458b (Osiris). The Rayleigh scattering by H2 molecules is seen in the near UV, the absorption by different layers of sodium around 6000 Angströms, and the detection of absorption by TiO and VO molecules around 7000 Angströms.

Moreover, from this measured visible spectrum, we have computed the colors that one could see by watching the sky and the star set from the planet itself (Figure 1.4). A short movie ("Star Set") has been produced as support for a CNRS press release on the results of our analysis of HST observations (see "A cyan disk in a purple sky: sunset over Osiris").

__Figure 1.4.__ Simulation of a sunset as seen from Osiris.



Imagine you are in a balloon floating in the atmosphere of the extrasolar planet HD209458b, or Osiris. The star is very close and is 20 times larger than the Sun seen from the Earth. The light scattered by sodium in the upper atmosphere gives the sky a purple color. The balloon moves away by the rapid winds; the star approaches the horizon, becomes less dazzling and turns cyan. When this gigantic sun sets, it changes into the color green, floating in a purple sky above, cyan below. Then everything turns green, a darker and darker green leaving room for the night.

In conclusion, works in our team have given many new and unexpected results on the atmosphere and evaporation of extrasolar planets, both observationally and theoretically. In short, we have provided new constraints on the properties of the atmospheres of hot Jupiters. These developments initiate new questions, and we expect further progress, particularly with new telescopes such as the GTC (Grantecan) on which a major program of 20 observing nights is ongoing. An extensive program of over 100 HST orbits is scheduled in cycle 19 (PI D. Sing) and a program for the observation of the transit of Venus with HST has been accepted for June 2012. In the longer term, we are eagerly awaiting the next generation of ground-based (ELTs) and space (JWST) telescopes.

1.3 Search for Radio Emission from Extrasolar Planets

The detection of the radio emission from an extrasolar planet would be a major step in the characterization of these planets and their environment. It could provide information on the planetary magnetic field and the interaction of the planet with the stellar magnetic field and the corona.

There have already been some searches for radio emission in the decametric domain (f < ~80 MHz) from a few extrasolar planets (see the review of Lazio et al. 2010), yet so far always with negative results. However, such a radio detection from the closest extrasolar planets is currently feasible, if these planets emit a flux 103 to 104 times larger than that of Jupiter. Such a detection may be possible pairing the extreme conditions of “hot Jupiters” with the scaling laws for radio emission (Zarka et al. 2001). All theoretical estimates of the maser cyclotron decametric emission, however, involve several unknowns, as for instance stellar winds, coronal density, stellar and planetary magnetic fields.

The main noise contributors at these low frequencies are sky background, radio interferences and ionospheric scintillation. Therefore, interferometric observations at high sensitivity and high resolution are very promising. Thus, the Giant Metrewave Radio Telescope (GMRT near Khodad in India), an interferometer of 30 km with 30 antennas of 45 meters in diameter each, appears well suited. We therefore undertook an extensive program to search for radio emission. It is based on the original idea of using eclipses of transiting planets by the star to discriminate any planetary emission against possible contributions from the star or the background.

We have performed observations of several planets (“hot Jupiters” and “hot Neptunes”), in several frequency ranges (e.g. 244 and 614 MHz, Lecavelier des Etangs et al. 2009, or 150 MHz, Lecavelier des Etangs et al. 2011). For HD189733b, we obtained upper limits with an improved sensitivity by more than one order of magnitude compared to previous observations. For HD209458b, observations also give a negative result with an upper limit of ~2mJy at 150 MHz.

The program continues and 6 other planets have been observed at 150 MHz. At the time of writing (mid-2011), encouraging results are emerging.

1.4 Outlook

A foresight exercise is certainly very useful for putting a research work in the context of a long-term strategy. However, one has to keep in mind that this is by no means a commitment, because it is expected that future work will generate enough discoveries and surprises to justify a reorientation of research; unthinkable questions today will hopefully appear tomorrow.

Atmospheres of Extrasolar Planets:

We plan to constrain both the extended atmospheres of evaporating planets and of atmospheres at lower altitudes – not only of giant planets but also of smaller mass planets. We will perform absorption spectroscopy during transits, either by using the best telescopes available – several programs are already underway on the Gran Telescopio Canarias (GTC 10.4 m) and the Hubble Space Telescope (HST) – or by expanding the sample of detected and analyzed exoplanetary atmospheres.

20 nights on the GTC have been alloted for fast photometry with the frontline instrument "Osiris." The unprecedented size of the sample thus surveyed will pave the way for a comparative exoplanetology. A result has already been obtained: the first discovery of potassium in the atmosphere of an extrasolar planet, the hot Jupiter XO-2b (Sing et al. 2011).

Six programs have been accepted on HST (STIS and COS) in order to better constrain the structure, dynamics and composition of the atmospheres of hot Jupiters, in particular the escape rate and evaporation mechanisms. A large program which has also been accepted on HST (over 100 orbits) will probe the atmosphere of more than ten exoplanets. In the long run, we will use the ELT from the ground and JWST from space to learn about the profiles of temperature, pressure and abundance on the largest possible range of altitude. In addition, we will further develop theoretical models of the evaporation of hot Jupiters to better constrain their evolution according to their diversity.

Search for Radio Emission from Extrasolar Planets:

The preliminary results obtained with the GMRT (India) are extremely encouraging. However, the mechanisms of radio emission can be very diverse, and the magnitudes of key quantities such as stellar and planetary magnetic fields are completely unknown; therefore, it is necessary to survey a large number of targets for covering the wide variety of exoplanets. Similarly, the extreme directivity and temporal variability of radio emission imply the coverage of the entire orbital period. Finally, the frequency of the cyclotron emission essentially depends on the unknown planetary magnetic field; thus, the frequency coverage should be as broad as possible. The GMRT offers unrivaled sensitivity from 150 MHz to 1.4 GHz. At lower frequency, Arecibo or URT2 should be considered. In the long term, LOFAR will provide unprecedented sensitivity and wavelength coverage.

Radial velocimetry:

We intend to pursue our use of the radial velocity method, especially with the SOPHIE spectrograph at OHP. Its recent optimizations open at least 5 years of observation, in particular searching for and studying low mass planets. Searching for long-period planets can be further extended by taking advantage of observations available since 1994 thanks to ELODIE. SOPHIE will also be involved in a radial velocity follow-up of photometric surveys, including the TESS mission of NASA, for which we have an agreement with the PI. We will continue to be involved in the programs carried out with HARPS at ESO-La Silla, and with instruments soon available such as ESPRESSO on the VLT and HARPS-N in the Canaries. Finally, we are involved in the development of SPIRou, an infrared spectropolarimeter to be installed at the focus of the CFHT in Hawaii. It will allow us to conduct several programs searching for and characterizing extrasolar planets around M dwarfs. These targets are particularly favorable for detecting low mass planets that are transiting in the habitable zone of their parent star.

Stellar and Planetary Physics and Extra-Solar Planets

2

The research team "Stellar Physics, Planets and Extra-Solar Planets" consists of:

7 CNRS researchers: Jean-Philippe Beaulieu, Lotfi Ben-Jaffel, Claude Bertout, Serge Koutchmy (emeritus), Jean-Pierre Maillard (emeritus), Jean-Baptiste Marquette, Juan Zorec

2 Faculty members (UPMC): Arnaud Cassan, Caroline Terquem

1 Researcher from CEA (emeritus): Thierry Montmerle (UMPC contract)

1 assistant engineer: François Sèvre

From 2007 – 2011:

7 Doctorates: Adel Auiti (co-direction IAP-Université de Sétif, Algérie), Cyril Bazin (joint supervision IAP-Université de Marseille), Omar Delaa (joint supervision IAP-Université de Nice), Philip Galli (joint supervision IAP-Université de Sao Paulo, Brazil), Thierry Semaan (IAP supervision), Jean Teyssandier (IAP supervision), Frédéric E. Vincent (IAP supervision).

4 defended PhD theses: Suleiman Baraka, Virginie Batista, Ehsan Tavabi (IAP co-supervision), Frédéric Vincent

HDR: 8

Publications: I: 149, II: 179

2.1 Gravitational Microlensing

Amongst the different methods to search for exoplanets (e.g. radial velocities, transits), gravitational microlensing is so far the only method able to detect low-mass planets (Neptunes, super-Earths) at large orbits (several astronomical units) from their parent stars. Hence, in spite of the relatively low number of discoveries (thirteen exoplanets have been published until the end of 2011), its unique sensitivity makes it an inescapable method to probe the full planetary mass and orbit regimes.

IAP has been conducting the international PLANET Collaboration (Probing Lensing Anomaly NETwork, http://planet.iap.fr) since 2002. It includes around 40 permanent collaborators from 10 countries worldwide. Observations rely on a telescope network of four permanent professional telescopes in the Southern Hemisphere (South Africa, Chile, Tasmania, Australia) and up to 20 additional telescopes, professional and amateur, working on alert mode. On the French side, PLANET was operated between 2007 and 2011 funded by the ANR HOLMES grant.

The most striking exoplanet detection by PLANET was the milestone discovery OGLE 2005-BLG-390Lb (Beaulieu et al. 2006), the first cool super-Earth (5 times the mass of the Earth, at 3 AU) ever found by any observational technique. Other important detections (in collaboration with other teams) include a Jupiter-Saturn Solar System analog (Gaudi et al. 2008); a cold Neptune also monitored from space to constrain parallax effects with the DEEP IMPACT spacecraft (Muraki et al. 2011); a number of Jupiter-like planets (e.g. Dong et al. 2009, Batista et al. 2011) and Neptune-like planets (Sumi et al. 2010, Miyake et al. 2010); and a very low-mass planet of only 3 Earth masses orbiting a very low-mass star (Bennett et al. 2008, Kubas et al. 2011). IAP is involved not only in analyzing events, but also in developing new modeling tools for the efficient extraction of physical parameters and real-time modeling (Cassan et al. 2010, Kains et al. 2009, Cassan 2008).

Microlensing is also a tool very well suited for statistical studies, because its sensitivity is almost not biased towards larger planet masses, as is the case for other techniques. In partnership with the (US-based) microFUN Collaboration, we first conducted a statistical study based on a homogeneous sample of very high-magnification events (Gould et al. 2010), from which an estimation of the normalization of the planetary mass function around the mass of Saturn was derived. Second, we lead an original statistical study based on all planet detections and non-detections from the observing seasons 2002-07 of PLANET(Cassan et al. 2011, accepted Oct. 2011, Nature, in press). We were able to constrain the wide planetary mass function for orbits between 0.5-10 AU and masses between 5 Earths and 10 Jupiters (results are described in Figure 2.1). From the mass function, we find that, on average, 17% (error bars: +6%,-9%) of stars host a gas giant planet (0.3 to 10 times the mass of Jupiter). Low mass planets are found to be even more common: their abundance per star is respectively 52% (error bars: +22%,-29%) and 62% (error bars: +35%,-37%). The average number of planets per star is thus greater than one. Planets in the Milky Way are the rule rather than the exception.

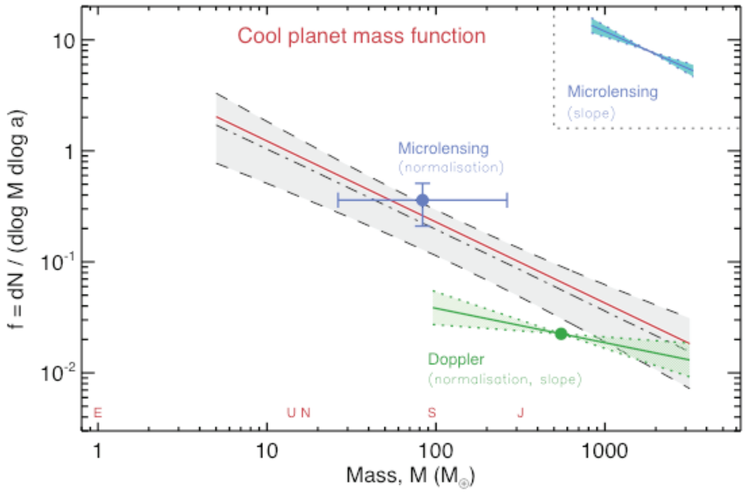


Figure 2.1. *Cool planetary mass function (red line, 68% confidence interval gray) for planets between 0.5-10 AU and masses between 5 Earths and 10 Jupiters as revealed by microlensing. Planets around stars are the rule rather than the exception, and low-mass planets, such as super-Earths and Neptunes, are found to be around six times more frequent than giant planets.*

2.2 Characterization of Extra-Solar Planets

Hot Jupiters enable us to probe the properties of their atmospheres. For those having passed in front of the host star, we can estimate their radius and mass by combining the radial velocities and transit characteristics, but mostly we can study the physical properties of their atmospheres. During a primary transit (planet passing in front of the star) it is possible to determine molecular abundances in the planetary atmosphere and the presence of clouds, while during a secondary transit (planet passing behind the star) we can observe the diurnal aspect of the planetary atmosphere. The emission spectra thus obtained are sensitive to the thermal structure of the atmosphere and to the presence of clouds. From the photometric data obtained with the SPITZER satellite of HD189733b, we have acquired the first ever detection of molecules in an extra-solar planet: the presence of water vapor (Tinetti et al. 2007, Beaulieu et al. 2008, Beaulieu et Tinetti 2008, Tinetti et Beaulieu 2008, see Figure 2.2.). This was later confirmed by Swain et al. 2008. Several subsequent studies then also announced the presence of methane, carbon monoxide and CO2. Using SPITZER data, we have also detected water vapor in HD209458b. We now have spectra from 0.5 to 24 microns obtained with different instruments and consistent modeling tools. This is a highly competitive and challenging topic with excellent new prospects.

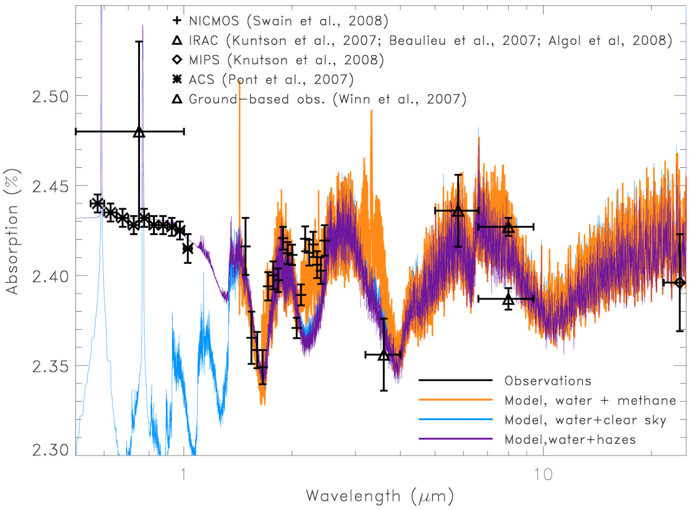


Figure 2.2. Transition spectrum of HD189733b from 0.5 to 24 microns. Different sets of data are used to cover a large wavelength interval, obtained with different instruments which produce consistent results. In the mean-IR we see the absorption spectrum of water, and we note the contribution from methane in the 1.5-2.5 micron interval. At shorter wavelengths, clouds and/or aerosols flatten the spectrum (micron model particles). The ECHO satellite will take spectra from across the entire range of wavelengths from 0.4 to 16 microns at resolution R=300.

2.3 Dynamics of Protoplanetary Discs and Extra-Solar Planets

Protoplanetary disks. We have studied the structure of disks containing "dead zones," in which no instabilities can develop. In the rest of the disk, either gravitational or MHD instabilities are maintained, which result in the disk material being accreted onto the central star. Our work has shown that such disks may be in a steady state, if mass can be transported in dead zones due to activity in the neighboring regions. Dead zones are a more favorable place for planet formation, since they are more massive, thicker and hotter than fully active disks (Terquem 2008).

Planet formation. By means of N-body simulations, we have computed the evolution of a system of 0.1-1 earth mass planetary cores embedded in a disk. The orbits of the cores are perturbed because of mutual gravitational interactions, so that the cores collide with each other and grow in mass through accretion. At the same time, migration through the disk occurs, and because the drift velocity depends on the mass of the cores, they capture each other in mean motion resonances. The simulations therefore typically end up with a few super-Earths or Neptunes on short period orbits which are nearly commensurable. This work predicts that a planet in this mass range which is close to its parent star should not be isolated (Terquem & Papaloizou 2007). This prediction seems to be confirmed by the observations of the Kepler satellite that were released in 2011. When the innermost planet is close enough to the central star that tidal interaction becomes significant, departure from exact commensurability occurs, but the planets stay dynamically coupled (Papaloizou & Terquem 2010). This is also confirmed by the Kepler observations which show a large number of systems close to mean motion resonances.

Planets on inclined orbits. Through the detection of the Rossiter-MacLaughlin effect, observers have shown that some planets are on an orbit which is inclined with respect to the equatorial plane of the star, and therefore to the disk that surrounded the star when it formed. C. Terquem and a student have studied the dynamics of such planets and found, rather to their surprise, that under some circumstances the gravitational potential from the disk could lead to a Kozai cycle in which the eccentricity and the inclination of the planet's orbit vary periodically (Terquem & Ajmia 2010). Jean Teyssandier continues this study in his thesis which he started in October 2011.

Atmospheres of planets. During a long-term visit to Princeton University in 2011, C. Terquem and a postdoc from IAS studied the structure of the atmosphere that forms around low mass cores embedded in protoplanetary disks. The study shows that the atmosphere fills in the Roche lobe of the protoplanet even if it is larger than the Bondi radius (Terquem & Heinemann 2011). This is in contrast to commonly used models in which the atmosphere cannot extend beyond the Bondi radius and is surrounded by a Bondi type flow.

2.4 Atmospheres of Planets and Exoplanets and Planet-Star Local Interstellar Medium Interaction

Our past studies, respectively on planetary atmospheres and the interaction between solar wind and the local interstellar medium, motivated us to initiate a global approach to handle the planet-star-LISM system through the projects INSPIRE and ESINPLE (particles-in-cell [PIC] 3D code, MHD 3D code, etc.; see projects section). These tools are also applied to extra-solar planets with the appropriate ISM environment. This proposed approach also forms the basis of the academic programs SWEP and FORREST, both oriented toward southern Mediterranean countries (see teaching/education section). The period 2007-2011 was rich in multidisciplinary applications and software development:

- Accurate measurement of the ISM magnetic field (LIMF) in the vicinity of the solar system. Confirmed by different observations, the LIMF obliquity is established (~40°) as initially reported and later confirmed by our team (Ben-Jaffel et al, 2000; Ratkiewicz 2008; Strumik et al, 2011).
- First detection of super-thermal atoms (OI & CII) in the extended atmosphere of exoplanet HD 209458b (Ben-Jaffel & Hosseini, 2010).
- PIC 3D simulation of a terrestrial magnetosphere (Baraka and Ben-Jaffel, 2007,

2011). The tool is used for academic training in the context of SWEP and FOR-REST projects. SWEP is supported by MAE (2004-2007 & 2011-2013), and IAP participates in the astrophysics chair allocated by UNESCO to Gaza's universities (2011-2015). The PIC code is also used to study the magnetosphere of extra-solar planets. This electromagnetic coupling was observed for the first time by HST (Clarke et al. 2002, see Figure 2.3).

Figure 2.3. *PIC 3D simulation of the Io-Jupiter system. The "donut" structure is the Io torus observed from above. The cloud of particles crossing the torus (left) and connecting its center (Jupiter's position) to outer regions is naturally obtained by the transport of particles between the Io satellite and the planet's poles along field lines. The same coupling is expected between exoplanets and their nearby stars.*

2.5 Wide-Field Spectra-Imaging for the Study of Star Forming Regions

From the applications of 3D-spectroscopy with an Imaging Fourier Transform Spectrometer (IFTS) started at the Canada-France-Hawaii telescope, the development has been focused on the wide-field capabilities of this technique, through several projects:

- Proposal of a space mission, a Molecular Hydrogen Explorer (H2EX), in response to the ESA Cosmic Vision call to conduct wide-field surveys in the first H2 rotational lines (9 – 28.5 μm);
- Study of a 1.8 – 5.5 μm IFTS as main instrument of a 2.5-m telescope at Dome C, within the European ARENA network for the development of astronomy in Antarctica ;
- A visible (350 – 900 nm) IFTS (12'x12' FOV), for the CFH telescope, SITELLE, in collaboration with U. Laval (Quebec), to study various types of extended emission line regions. The instrument will be delivered the first semester of 2013;
- A review paper "Wide integral field spectroscopy in astronomy: the Imaging FTS solution" (Maillard et al., Experimental Astronomy, submitted).

2.6 High-Resolution Spectroscopy of Planetary Atmospheres

For the first time the wind velocities in the Jovian thermo-sphere have been determined from the auroral emission of H2 and H3+ observed with the CFHT Imaging FTS, showing a difference of 1.7 km/s between the neutral and the ionized wind, indicative of the upper atmosphere structure (Chauffray et al. 2011).

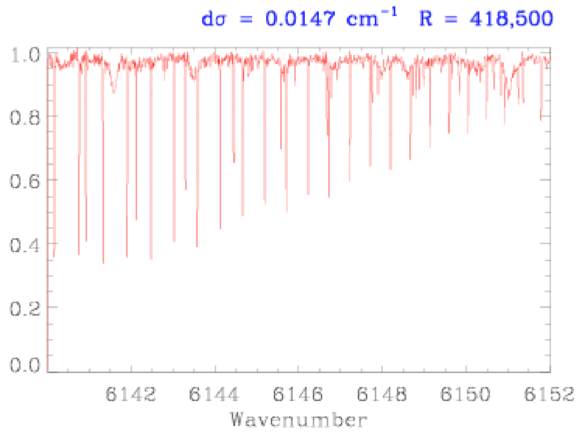


Figure 2.4. *Isotopic ratios $^{13}C/^{12}C$ and $^{18}O/^{16}O$ are indicators of the escape history of the Martian atmosphere. The most precise determination of these ratios has been obtained from a very high-resolution spectrum of Mars in a CO^2 band (6022 – 6308 cm-1) with the CFHT- FTS indicating an enrichment of the heavy isotopes (Krasnopolsky, Maillard et al. 2007).*

2.7 Fundamental Parameters of Pre-Main Sequence Stars

Bertout and collaborators have been studying the kinematics of star forming regions with the aim to derive individual parallaxes for the members of nearby T associations, for which only average distances are usually known. In a first investigation, Bertout and Genova developed a variant of the classic convergent point method that was optimized to studying young associations characterized by relatively large internal velocity dispersion and inhomogeneous clustering in space. They successfully applied the method to the Taurus-Auriga star-forming region and derived individual parallaxes for 67 moving group members with known radial velocity. Using the new distances, Bertout, Siess and Cabrit re-derived improved estimates of the ages and masses of the young stars and found a relationship between the age of the stars and the presence of circumstellar disks (Figure 2.5).

Such a relationship was expected but had never been demonstrated earlier, presumably because the average distance to Taurus used in earlier investigation blurs the derived ages and masses. It confirms that disks are most likely present in all forming stars and become depleted in time by accretion of matter onto the star and/or dissipation because of planet formation. The study of Taurus-Auriga was based on radial velocities found in the CDS databases, and it turned out that the accuracy of the derived distances was affected by the inhomogeneity of the various measurements. Observations of southern star forming regions using the FEROS instrument on the 2.2m ESO telescope were therefore planned and carried out by Galli, Teixeira, Ducourant, and Bertout. Meanwhile, Galli and the same collaborators came up with a new implementation of the convergent point method that explicitly utilizes the fact that members of stellar moving groups move along great circles on the sky to improve the performances of the convergent point algorithm. This new method is currently being used to reanalyze an extended sample of T Tauri stars in Taurus-Auriga. The radial velocity data obtained at ESO for Lupus and Ophiuchus stars are also currently being used to study the kinematics of these two regions and derive individual parallaxes for the members of these associations. A comparison of protoplanetary disk lifetimes in different environments will then be possible, with implications for the timescales of planet formation.

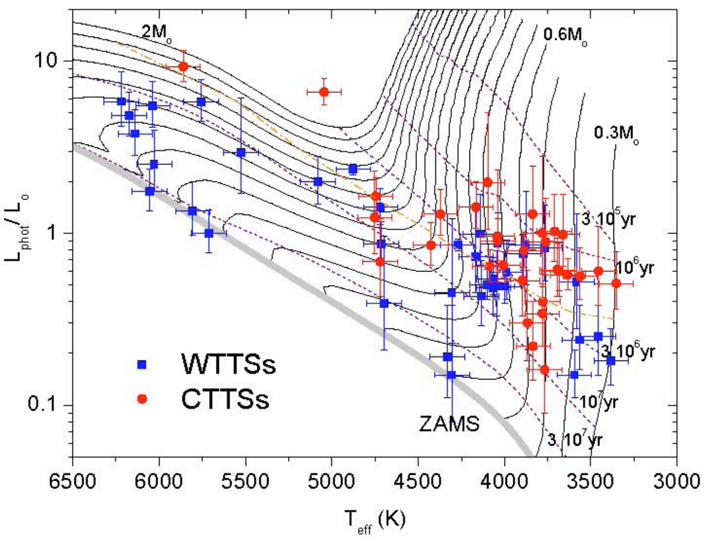


Figure 2.5. *Hertzsprung-Russell diagram of the Taurus-Auriga moving group stars. Red dots denote classical T Tauri stars (CTTSs) surrounded by protoplanetary disks and blue squares mark weak-line T Tauri stars (WTTSs) with no evidence for the presence of protoplanetary disks. The error bars indicate the 1σ uncertainties on the photospheric luminosity Lphot and the effective temperature T_{eff}. The solid black lines are evolutionary tracks, computed with Y = 0.277 and Z = 0.02, for stars with masses ranging from 0.3 to 2 solar masses with a mass increment of 0.1 solar mass. The current position of the Sun as computed with these parameters is shown as a solar symbol.*

Note that the parameters chosen for the computation of pre-main sequence evolution tracks are not solar, so that the properties of the computed 1 solar mass model do not exactly correspond to those of the actual Sun.

2.8 High-Energy Phenomena in Young Stars and Massive Star Forming Regions

Stellar X-ray emission. T. Montmerle has been the PI of an XMM "Large Program" on the T Tauri "twin binary" system V4046Sgr (two stars of about 1 solar mass, separated by ~ 2.5 solar radii, and surrounded by a circumbinary accretion disk). The purpose was to look for an orbital rotational modulation of the accretion, guided by the complex magnetosphere of the system. We could detect this modulation, and distinguish it from the random flaring activity, and, with the help of coordinated observations with CFHT/Espadons, we could determine the magnetic topology of the system (Argiroffi et al. 2011, Donati et al. 2011).

In another context, T. Montmerle was involved in a Chandra "Very Large Program," consisting of a 22-field mosaic of the Carina nebula, covering ~ 1.4 sq. deg. Many results were obtained (see below), in particular a study of hierarchical star formation in clusters (Feigelson et al. 2011, Getman et al. 2011).

Diffuse X-ray emission as feedback from massive stars. The same Chandra program revealed an intense, diffuse X-ray emission in the Carina nebula, corresponding to a hot plasma created by stellar winds and past supernova explosions (Townsley et al. 2011a,b). Based on this result, we looked into the possibility that a supernova shock could be responsible for the abnormal properties (high temperature and luminosity) of the dust emission observed by Spitzer in the Eagle nebula (M16), but this proved unsuccessful (Flagey et al. 2011). Such feedback effects from massive stars also exist on galactic and extragalactic scales (Montmerle 2011a).

Gamma-ray sources, supernova remnants, and ionization of molecular clouds. It is now well established that a class of high-energy gamma-ray sources are associated with supernova remnants interacting with molecular clouds, as a result of pp → p° interactions between in situ accelerated cosmic rays (> 1 GeV) and molecular material (Montmerle 2011b). We have investigated the correlated low-energy cosmic-ray effect, namely the possibility of enhanced molecular cloud ionization. Using various molecular ionization tracers, we have indeed detected for the first time with the IRAM 30m telescope a ~100-fold enhancement in a molecular cloud associated with a HESS TeV gamma-ray source (Ceccarelli et al. 2011, Figure 2.6).

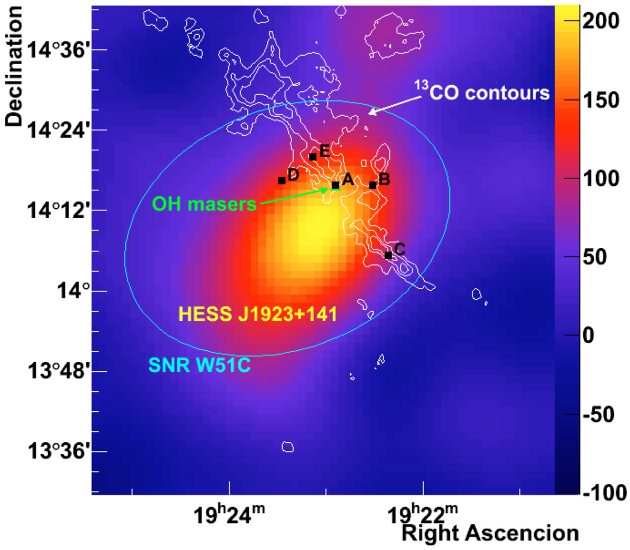


Figure 2.6. *Example of interaction between a supernova remnant ("SNR:" W51C) and a molecular cloud (C^{13}O contours), which explains the γ emission (TeV barely resolved) detected by the HESS telescope. This emission is due to pp collisions between the cosmic high energy radiation accelerated by the shock front from the SNR (shown by an OH maser), and the cloud. Millimetric observations (sight lines "A" to "E") indicated for the first time an over-ionization by a factor 100 in this cloud, which is produced by the component of low energy of the same cosmic radiation.*

2.9 Eros

A number of microlensing dark-matter surveys have produced tens of millions of light curves of individual background stars. This data provides an unprecedented opportunity for systematic studies of whole classes of variable stars and their host galaxies. One interesting result was to use the EROS-2 survey of the Magellanic Clouds to detect and study the population of beat Cepheids (BCs) in both Clouds. This project is described in chapter 7.3.4.

2.10 Massive and Intermediate-Mass Stars

Rapid rotation. Rapidly rotating massive and intermediate-mass stars can develop extended convective zones in their external layers, which otherwise are radiative in non-rotating ones. As a consequence, differential rotation is favored, which not only produces particular macroscopic broadening of spectral lines, but does change the geometry of the photosphere (Zorec et al. 2011a). Combined spectroscopic and interferometric studies are currently carried out to study the surface rotation law of these stars, which is an outstanding signature of angular momentum redistribution processes that are today still barely known (see Figure 2.7).

Our studies on the evolution of rotational velocities, based on several thousands of O, B and A-type stars, clearly indicate the existence of the differential rotation predicted above (Zorec and Royer 2011, Zorec et al. 2012). They have also underlined difficulties of rotating-star models to explain the observed rotational behavior of Main Sequence stars.

Progenitors of LGRBs. We have shown that Be stars of initial low metallicity can be progenitors of "collapsars," a possible mechanism to produce long gamma ray bursts (LGRBs) (Martayan et al. 2007, 2010).

Circumstellar environments, Be and WR stars. Several international observational follow-up campaigns were carried out to study the wind interaction phenomena in WR stars (Fahed et al. 2011). Interferometric observation and spectroscopic analysis of FeII emission lines revealed that the circumstellar envelopes of Be stars have large height perpendicular to the equatorial plane in spite of their quasi-Keplerian rotation (Zorec et al. 2007, Kanaan et al. 2008, Delaa et al. 2011).

Giant telescopes and the stellar fundamental parameters. The new generation of giant telescopes will enable us to observe individual stars in other galaxies. The first characterization of these objects can be obtained with low-resolution spectra around the Blamer discontinuity (BD). To this end, we have produced new calibrations of stellar fundamental parameters as a function of the height and the mean spectral position of the BD, which are both independent of interstellar and circumstellar emissions/absorptions, and both well resolved indicators of the effective temperature and bolometric luminosity. As shown in previous works for Be stars, we have shown that the BD can be a useful tool to study chemically peculiar stars (Cidale et al. 2007).

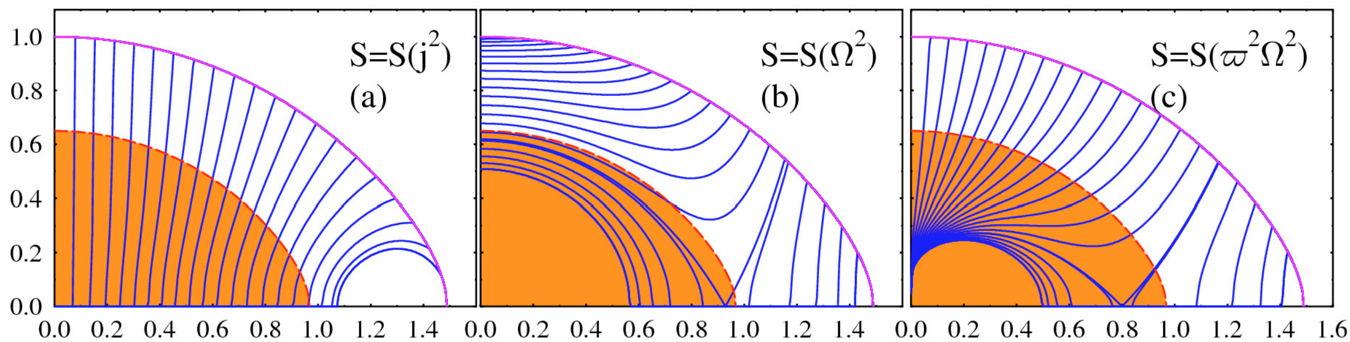


Figure 2.7. *Iso-angular velocity lines (blue) calculated by imposing: a) surfaces of entropy parallel to those of specific angular momentum; b) parallel surfaces of entropy and angular velocity; c) parallel surfaces of entropy rotational energy. The shape of the star depends on the surface angular velocity law Omega=Omega(theta).*

2.11 Peculiar Binary Stars and Fu Orionis-Type Stars

Work on symbiotic binaries has been done (Friedjung 2007), information obtained about stratification of the winds of their cool components (Friedjung et al. 2010) and on the emission lines of the symbiotic Mira RR Tel (Kotnik-Karuza, Friedjung and Exter 2009). We also looked at evidence for the presence of winds of novae and their nature soon after the explosion. The spectra of the old nova

HR Del indicate the presence of a hot spot on its disk (Friedjung, Dennefeld et al 2010). The binarity of the B[e] star MWC 314 (Muratorio et al. 2008) was later confirmed and evidence was found for an inclination of the axis of rotation of the visible component with respect to that of the accretion disk.

Several new FU Orionis class objects have been followed spectroscopically with the aim of studying their evolution (Senkov et al. 2010, 2011).

2.12 Solar Magnetism and Heliophysics

Research on surface solar magnetism is taking advantage of the analysis of spectra showing both absorption and emission lines, mainly above the limb. Beside the surface magnetic field, this analysis also permits deducing the velocities, both convective and turbulent, and the associated temperatures. This work is now considerably improved thanks to the results coming from space missions such as SoHO, Trace, Hinode, Stereo, and SDO, which focus on White-Light (W-L), EUV and soft X-rays (SXR) radiations. 1D models are still of use, but the analysis of structures is the core of our approach, starting with the transition region photosphere-chromosphere-corona. Accordingly, we extend our investigations to EUV and SXR regions. Prominences, spicules, loops, X-ray jets, and linear W-L rays are studied, as well as large scale phenomena leading to Coronal Mass Ejections. The magnetic field is inferred from the behavior of plasma structures. In some cases, it is compared to model predictions computed from the measured surface magnetic fields using the Potential Field Source Surface (PFSS) model. In fact, a multi-scale approach is used to interpret our observations, including eruptive phenomena from both coronal holes and active regions (jets, spicules, plasmoides etc).

We used new eclipse observations (2008- 2010) from the slitless spectroscopic method and the polarimetric W-L imaging of the corona, as well as specially devoted space-borne observations taken around the time of totality, allowing us to deduce new original results. These include the precise analysis of the solar limb (Figure 2.8), in support of the French Picard mission, and the discovery of polarization neutral points in the eclipse corona field. In addition, we analyzed dynamical events of the magnetized plasma corona as part of the newly emerging Helio-physics with its application to Space Weather.

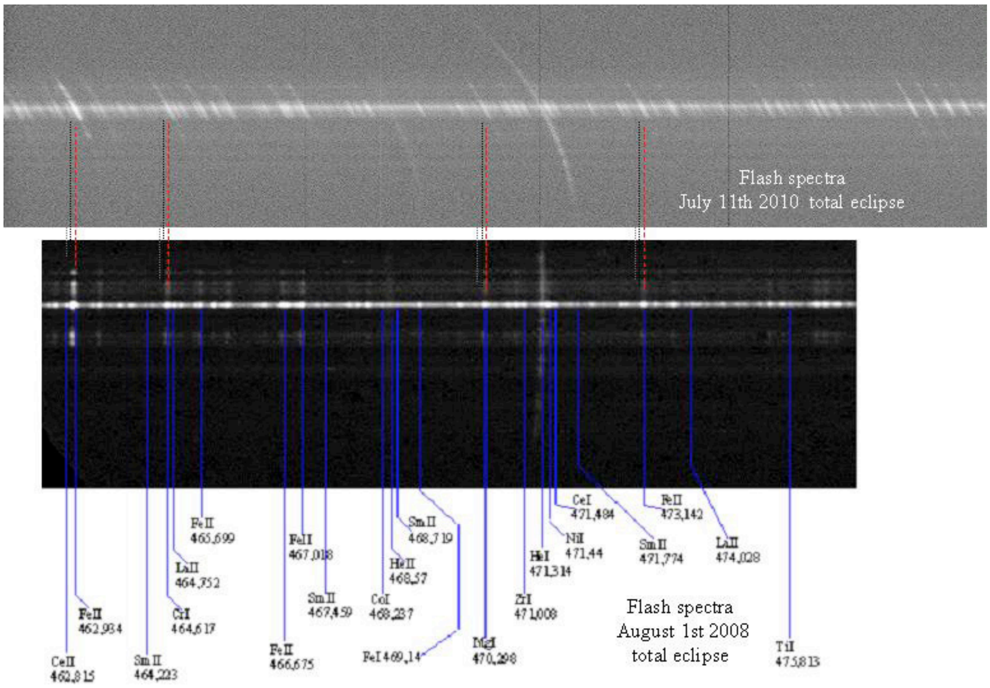


***Figure 2.8**. Extract of flash spectra (top: eclipse of 11. Jul. 2010, bottom: eclipse of 1. Aug. 2008). Numerous small emission lines are seen. The chromospheric envelopes surrounding the Sun are those of HeI 471.3 nm, and for the first time (bottom) those of HeII 468.6 nm. Moon mountains and valleys modulate the intensity of line profiles. These lines of low intensity can only be observed during total eclipses. Spectra were obtained with objective gratings with 600 tr/mm, 600 mm of focal and CCD Lumenera.*

2.13 Outlook

On stellar physics, based on our expertise on massive stars, we are contributing to the GAIA mission. The search for surface differential rotation in massive and intermediate mass stars with combined spectroscopy and **VEGA/CHARA** interferometry will be actively pursued. This will be accompanied by modeling of spectra and interferometric data due to differentially rotating objects with consistent geometrical deformations and concomitant gravitational darkening. In the frame of **GREAT** (GAIA Research for European Astronomy Training) we actively participate by providing models of rotating stars with our calculation codes **FASTROT** and GIRFIT to analyze spectroscopic data form FLAMES/GIRAFFE at ESO/VLT of objects for which GAIA will provide parallaxes. Problems related with the angular momentum content in stars and star formation, are here envisioned. We are preparing detection criteria in the frame of **GAIA-Alerts** to unleash automatic spectroscopic follows up of targets with light outbursts, either in Be stars or SN.

Concerning the EROS project, the EROS-2 database (87 millions of light curves, 1.55 million of images) appears as an important test bed for massive data mining where we apply various statistical and automatic classification methods from now on arising in astronomy, in preparation for upcoming massive data sets for variable stars such as GAIA, Pan-STARRS and LSST.

On the other hand, with the acquired experience on Imaging Fourier transform spectrometers, in collaboration with Canadian partners, a new instrument for CFHT, SITELLE, working from 350 to 900 nm, on a 11'x11' FOV and a spectral resolution up to 10,000, available on the telescope by the end of 2013, will make possible global studies of the ionized zones of galactic HII regions, of nearby planetary nebulae.

In the future, work on exoplanets will be directed toward the search of new exoplanets using micro-lensing and the preparation of the ECHO mission if selected by ESA.

PLANET (30 scientists from 11 countries, led from IAP) a worldwide combined network of 45 telescopes performing coordinated observations and sharing data including feedback from nearly real-time modelling, based on gravitational micro-lensing technique, explores a unique niche: cold planets down to small masses orbiting around any kind of stars, free floating planets or exomoons. The next phase is a worldwide network of wide field imagers (5 square degrees SKYMAPPER telescope and new 1.3-m telescope in Tasmania) with science objectives preparing the programs on board the EUCLID and WFIRST missions.

We will study also the characterization of extra-solar planets. Using optimal pipelines developed for micro-lensing, our team was successful in making observations that have given us real insights into the composition of some hot-Jupiters, before extending it to hot-Neptune. The natural extension has been to take a leading role in the preparation of the Exoplanet Characterization Observatory (ECHO) (pre-selected by ESA as an M3 mission). This project encompasses more than 260 scientists from France, U.K., Italy, Belgium, Germany, Portugal, Spain, and Hungary.

Regarding the Solar system activities, we will continue on solar physics and magnetospheres.

We plan extending SWEP & FORREST to other southern-Mediterranean countries. We also plan to apply ESINPLE (PIC and MHD 3D codes) to different families of exoplanets to study their atmospheres and plasma environments. Finally, a high-resolution interferometer will be proposed to CNES (micro-satellite, 2013) for mapping the sky background Lyman-α emission in order to monitor the heliosphere distortion due to the oblique ISM magnetic field and the variable solar wind.

Finally, using the data collected at the total eclipse in Polynesia 2010 and 2012 in Australia, we plan to work on i/ the solar edge and the solar diameter measurements, ii/ the transition regions of the chromosphere and of the prominence interface with the corona and iii/ on the corona using both spectroscopy and images collected from space missions.

Our research activity in the domain of disks and extra-solar planet dynamics will focus on the evolution of protoplanetary disks and the interaction between the disk and proto planets.

3

Origin and Evolution of Galaxies

The research group "Origin and Evolution of Galaxies" consists of:

5 CNRS scientists: Stéphane Charlot, Valérie de Lapparent, Daniel Kunth, Nicolas Prantzos, Jacques Roland

5 astronomers: Emmanuel Bertin, Michel Dennefeld, Florence Durret, Gary Mamon, Hélène Roussel

3 faculty members: Michel Fioc (UPMC), Damien Le Borgne (UPMC), Brigitte Rocca-Volmerange (U. Paris-Sud)

1 CEA scientist: Laurent Vigroux

From 2007 to 2011:

8 postdoctoral fellows: Paula Coelho, Benjamin Johnson, Yuko Kakazu, Susan Kassin, Sundar Srinivasan, Dylan Tweed, Jakob Walcher, Vivienne Wild

11 doctoral students: Hakim Atek, Anthony Baillard, Gwenaël Boué, Jacopo Chevallard, Elisabete da Cunha, Guillaume Drouart (co-direction ESO), Artur Hakobyan (co-direction Obs. Byurakan, Armenia), Jean-Christophe Mauduit, Camilla Pacifici, Dmitry Prokhorov (co-direction Inst. Physique Technologie Moscow), François Ricquebourg

6 doctoral theses were defended: Hakim Atek, Anthony Baillard, Elisabete da Cunha, Artur Hakobyan, Jean-Christophe Mauduit, Dmitry Prokhorov

1 "habilitation à diriger les recherches" was also defended: Valérie de Lapparent

HDR: 8

Publications: I: 329, II: 156

The study of the origin and evolution of galaxies is a central topic for the scientists at IAP. The aim is to understand the cosmic history of the different components of galaxies, namely stars, active nuclei, dust and gas. Fundamental questions about the origin and evolution of galaxies remain unanswered: Are the basic properties of galaxies acquired early on in the history of the Universe or more recently? What is the role of collisions and merging in establishing the morphological Hubble sequence? What is the influence of the galactic environment? What is the history of enrichment in heavy elements within the various types of galaxies? Are bursts of star formation a key element or only a marginal phenomenon? Which types of galaxies are preferentially detected at ultraviolet, infrared, submillimeter, and radio wavelengths?

Because the internal physics of galaxies are influenced by the surroundings (tidal effects, ram-pressure stripping, merging), the team's scientists study their properties in a large variety of environments, in particular groups and clusters. The research at IAP is based on observations that use a large diversity of instruments in ground-based (CFHT, ESO/VLT, IRAM, VLBI) and spatial (XMM-Newton, Chandra, GALEX, HST, Spitzer, Herschel) observatories. Several theoretical models and simulations have been built in parallel and are used to analyze data from these observatories: codes of spectral synthesis and chemical evolution of galaxies, models of kinematic analysis of galaxies and galaxy structures, models of merging clusters of galaxies, and models of radiogalaxy nuclei with supermassive black holes.

By observing the spectral energy distribution of galaxies at all wavelengths (X-ray, ultraviolet, visible, infrared and radio), and thanks to the interpretation with theoretical models, the observational data aim at better understanding the history of mass accumulation in galaxies, via the assembly of the dark matter halos, the accretion and ejection of gas, and the formation of stars. The role of energetic (active nuclei, radiogalaxies), and dynamical phenomena (collisions, internal instabilities) also needs to be elucidated.

3.1 Internal Physics of Galaxies

One of the strong points of the "Origin and Evolution of Galaxies" group at IAP is related to the study of the physical processes operating in the galactic components: gas, dust and stars in disks, bulges, halos and active nuclei. In the past few years, it was necessary to take into account the interactions among these various components. Studies of the chemical composition of the Milky Way and of other galaxies allow one to probe the various sites of nucleosynthesis and the epochs when the galactic components were assembled. Moreover, the main nucleosynthesis agents are the massive and intermediate stars, which considerably affect the state of the interstellar medium through chemical enrichment and ionisation. Star forming regions may then be used as tracers of galactic activity, making it possible to study the early stages of galaxy evolution, at high redshift.

In particular, the scientists in this group study the interplay between star formation and the interstellar medium as one of the fundamental drivers of galaxy evolution. Among the most important processes are heating and cooling mechanisms of gas and dust, and metal enrichment. The scientists strive to obtain a coherent view of galactic physics by means of multi-wavelength observations of stellar and interstellar phases, on all spatial scales from star formation complexes to clusters of galaxies. The radio emission, which allows one to uncover the interplay between the formation and galactic evolution and the phenomena at the center of active galaxies (active nuclei, radio jets), also plays a key role. Moreover, the scientists in this group make a significant contribution to the statistical studies of supernovae as a function of the host galaxy properties, a subject of dazzling developments in the past years.

3.1.1 The Milky Way

3.1.1.1 Positron Emission

The Galactic emission at 511 keV, resulting from positron annihilation, has been known since the early seventies, but its morphology has only been revealed in the last few years from observations with ESA's INTEGRAL gamma-ray observatory: the bulge emission is stronger than the one of the disk, a situation that occurs at this wavelength only. Prantzos et al. (2011) reviewed all the observational constraints and potential sources and identified the propagation of low energy positrons in the magnetized plasma of the Galaxy as the key to the puzzle of this intriguing emission.

3.1.1.2 Chemical Evolution in the Local Group

According to the hierarchical merging paradigm, galaxies are formed through accretion and merging of smaller units, composed of stars and/or gas. Prantzos (2008) showed that the metallicity distribution of the Galactic halo can be calculated semi-analytically in that framework under plausible assumptions based on observations of the dwarf galaxies in the Local Group. A comparative study of the Milky Way and Andromeda (M31) showed diverging star formation histories for the two giants of the Local Group, a quiescent one for the former and a more active for the latter (Yin et al. 2009). In particular, M31 probably underwent a head-on collision with M32 about 200 million years ago, as corroborated by observations in the infrared.

3.1.2 Dust Cycle and Hidden Star Formation

The general aim of the Herschel programs on nearby galaxies and on star formation is to characterize the composition of the interstellar medium and its heating and cooling mechanisms, to enable the global dust and gas emission to be used as tracers of a few key physical properties, and to understand how star formation is coupled with the interstellar medium at all spatial scales (from individual HII regions in the Milky Way to kiloparsec scales within local galaxies). With Herschel, it becomes possible to build complete spectral energy distributions from resolved structures within galaxies and to extract regions dominated by either OB stars, intermediate stars, the diffuse interstellar radiation field, or an active nucleus.

One of the first results of the Very Nearby Galaxies Survey (P.I. C. Wilson) concerns the extended dust halo of M82, the closest starburst galaxy featuring a galactic wind, that is seen almost edge-on. From the temperature and density maps built from Herschel-SPIRE data, we conclude that as much as one fourth of the dust produced in M82 has been expelled from the disk and coincides mostly with tidal features (detected in atomic hydrogen) rather than the starburst wind. The gravitational interaction with the M81 group is thus much more efficient than the starburst feedback in enriching the intergalactic medium (Roussel et al. 2010).

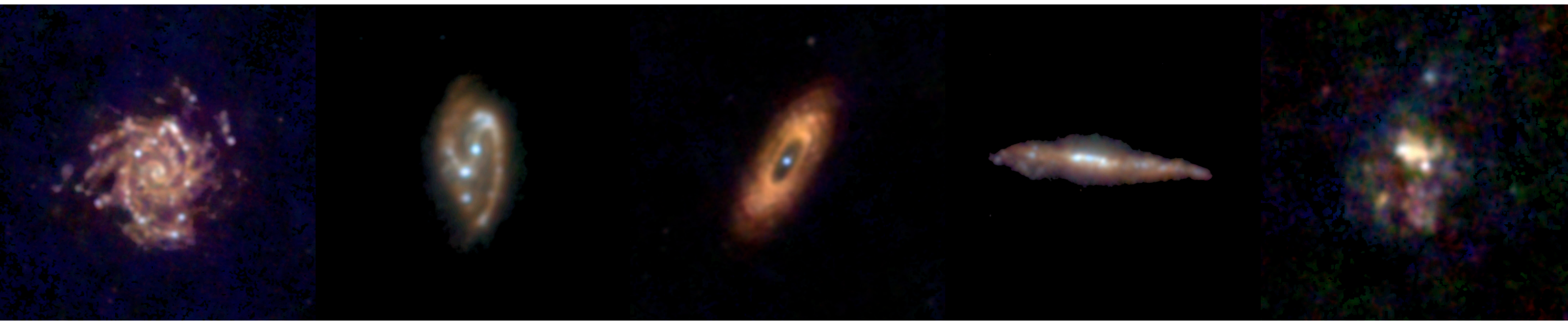


Figure 3.1. *Three-color images of a subset of the 61 galaxies of the KINGFISH key program (70, 100, and 160 μm in blue, green, and red). Blue regions highlight the presence of hot dust, in particular in HII complexes.*

For the KINGFISH program (Kennicutt et al. 2011), the maps from the PACS instrument (see Figure 3.1) that were released to the team were processed with Scanamorphos (map-making software for Herschel and similar scanning bolometer arrays, Roussel 2011). Our goal is to quantify the contribution from various stellar populations to dust heating by linking maps from the ultraviolet to the submillimeter with spectral evolution models (Johnson et al. 2007); to gauge what fraction of star formation is hidden by dust in different types of local galaxies; and to match their observed stars, gas and dust content with model predictions by carefully accounting for the role of AGB stars in the dust cycle. AGB stars are so abundant that they contribute significantly to the integrated infrared spectra of galaxies. They are key ingredients of population synthesis and chemical evolution models of galaxies: dust is produced in their thick envelopes and subsequently injected into the interstellar medium by radiation pressure. Srinivasan et al. (2010, 2011) have computed a comprehensive grid of radiative transfer models of AGB envelopes, that will be used in KINGFISH.

The study of the extragalactic proto-starbursts (Roussel et al. 2006) which are excellent candidates for hosting a dominant very young starburst (of the order of 1 Myr old) was also pursued. The infrared spectra of these galaxies are characterized by extremely high optical depths. To model them, a new radiative transfer code was developed, rigorously embedding the detailed optical properties of dust and all physical dependencies as a function of composition and grain size. It will be applied to the Spitzer spectra and Herschel photometry of the proto-starbursts in order to constrain the physical conditions, the geometry of the gas reservoir, and the dust properties in these peculiar environments.

3.1.3 Supernovae and Host Galaxies

A spectroscopic follow-up of several Supernovae (SNe) whose progenitors are massive stars is underway in an international collaboration, in order to better understand the explosion mechanisms and the subsequent evolution (e.g. Dennefeld et al. 2007, 2008). The influence of the circumstellar material on the spectral evolution has been demonstrated in one case (Pastorello et al. 2008), whereas a precursor eruption has been observed in another (Pastorello et al. 2007). This program will be amplified thanks to a "Large Program" granted by ESO (Smartt et al. 2011). Simultaneously, the preparation for the launch of the Gaia mission continues (cornerstone of ESA, launch foreseen in spring 2013), with the set-up of an alert mechanism to allow early detection and ground-based follow-up of new SNe. This requires the enrollment of adequate ground-based observing means, notably in spectroscopy, and tests of the alerts classification, which will be done thanks to actual alerts from other ground-based surveys. One of the goals will be, for instance, to obtain a homogeneous sample of closeby type Ia SNe, which would allow establishing the full dynamical structure of the local Universe, following the approach initiated by Colin, Mohayaee et al. (2011).

An analysis of the observations of 600 core collapse supernovae revealed that the frequencies of the various sub-types (SNII, SNIb/c) are correlated with both the global metallicity of the host galaxy and the local one at the explosion site (Boissier and Prantzos 2009). This result is interpreted mainly in terms of the evolution of rotating massive stars with mass loss, but the role of binaries remains difficult to assess. Moreover, this study revealed for the first time a significant and unexpected correlation between metallicity and the ratio of thermonuclear to core collapse supernovae (SNIa/CCSN, Boissier and Prantzos 2009). Finally, the "Supernova Legacy Survey" project found evidence for a dependence of the SNIa luminosity on galactic metallicity and, perhaps more surprisingly, on the age of the stellar populations of the host galaxies (Howell et al. 2009).

Many investigators focus on the properties of galaxies hosting SNe. Within a collaborative approach involving astronomers from the Byurakan Astronomical Observatory (BAO) in Armenia, the distribution of core-collapse SNe (type II, Ib and c) has been re-analyzed using a large sample from IR databases such as DENIS and 2MASS. The aim is to characterize the rate of SN formation in galaxies and the properties of the host-galaxies. The SN distribution is consistent with an exponential distribution in the disk but presents a stronger concentration for the SNIb/c than for the SNII ones, probably due to metallicity gradients within the disks (Hakobyan et al. 2009). Moreover, the properties of galaxies (total stellar mass, star formation rate) hosting Gamma ray bursts are investigated within the GHOSTS collaboration, thanks to a complete database and to modeling performed with the PÉGaSE code (see Sect. 3.3.1). Given the interest of these various results for the theory of stellar evolution, and in preparation of the future large surveys of SNe, the annual IAP colloquium (June 2010) was devoted to these subjects ("Progenitors and Host Galaxies of Stellar Explosions"). The colloquium was led by three members of the group.

3.1.4 The Lyman α Line in Nearby and Distant Galaxies

Investigations of the Lyman α lines in nearby galaxies as a way to discover primordial galaxies has been among the top priorities of the group for the past ten years. Results obtained with imaging and spectroscopy techniques using the ACS and STIS on-board the Hubble Space Telescope (HST), have emphasized the importance of kinematic effects which are generally overlooked in radiative transfer studies of the scattering of this line in the neutral interstellar medium. Owing to the excellent spatial resolution of Hubble as well as numerical simulations, our studies at very small scale show the importance of the porosity of the medium and that of the dust (Atek et Kunth 2008, Atek et al. 2009). A statistical study and a follow up of Lyman α emitters revealed by the GALEX satellite has, for the first time, provided evidence for the link between the escape fraction of these photons and the dust content (Atek et al. 2009). The way the choice of the Lyman α line impacts the selection of distant galaxies has subsequently been estimated (Hayes et al. 2010), and the Lyman α escape fraction was shown to evolve with redshift (see Figure 3.2). Kinematic effects on the Lyman α line were also explored observationally in the NaD line in absorption using FLAMES at the VLT. The IAP annual colloquium of July 2009 was devoted to "The Lyman α Universe" and chaired by three members of our team. Three workshops have been organized on this topic at IAP in 2007 and 2011.

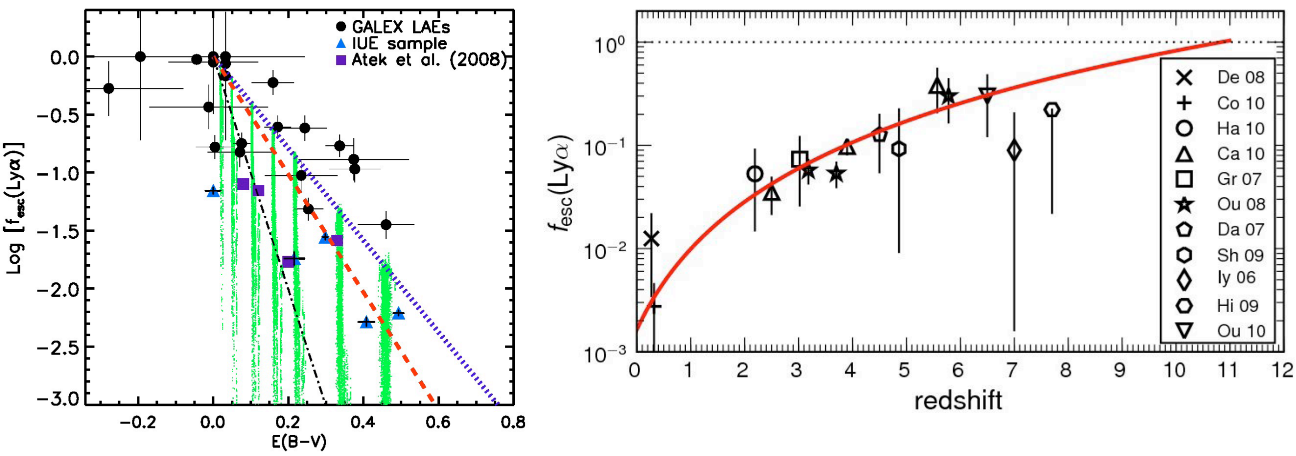


Figure 3.2. Dust dependance of the escape fraction of the Lyman α line (left), and its evolution with redshift (right); green dots (left) are galaxies simulated by a radiative transfer code.

3.1.5 Properties of Gas-Rich Starburst Galaxies

A comparison of data obtained from GALEX, Spitzer and Chandra for starburst galaxies indicates a good agreement between rates of star formation calculated in the UV and from X-rays. This shows that the X-ray luminosity is a good tracer of star formation in these galaxies, except in cases where an obscured AGN is responsible for the excess of X-rays (Rosa-Gonzalez and al. 2007).

Wolf-Rayet stars are a very important evolutionary phase of massive stars. Their presence is a signature of the mechanism by which bursts of star formation behave in so-called Wolf-Rayet galaxies. These stars are strong contributors to the heavy element enrichment of their interstellar medium. Members of our team have analyzed this problem using a sample of thousands of galaxies selected from the "Sloan Digital Sky Survey." The highlight of this investigation is to reveal a noticeable difference between the heavy element content of the ionized gas in Wolf-Rayet galaxies as compared to galaxies in which these stars are not observed (Brinchmann et al. 2008). In 2009, a workshop was organized at IAP on Wolf-Rayet galaxies.

Finally the composition of heavy elements as observed in HI is systematically less abundant than that of the HII gas. This discrepancy has been confirmed with the FUSE satellite and exemplified with the case of the gas-rich and bursting galaxy POX36 (Lebouteiller et al. 2009, Kunth and Lebouteiller 2011).

3.1.6 Radiogalaxies

IAP maintains a significant role in the field of radio galaxies, both with the analysis of individual objects and their role in the evolution of star formation.

3.1.6.1 Internal Modeling

The interpretation of complex objects such as radio galaxies can not be done without a detailed modeling of radio jets based on the VLBI components (intercontinental, interferometric observations) of compact radio sources. A member of the group has shown that one can model the complex ejection in the first millisecond of arc of the nuclei of radio sources. Measurement of the variations of the two coordinates of the ejected component allows one to find the angle of inclination of the radio source and the Lorentz factor of the ejected component. The complex trajectory can be explained if the nucleus of the radio source contains a binary system of super massive black holes. This binary system causes a double perturbation of the path of the plasma: the first perturbation is due to the precession of the accretion disk and the second to the motion of black holes around the center of gravity of the binary system. If the core of the radio source contains a binary system of super massive black holes, the two black holes may eject VLBI components, leading to two families of trajectories (Roland et al 2008). An important consequence of the presence of a binary system of super massive black holes can be deduced: the VLBI core is associated with one of the black holes and if the VLBI component is ejected by the second black hole, one can detect the shift of the origin of the ejection, which provides a direct measure of the size of the binary system. Within 100 microseconds of arc, the structure of the nuclei of radio sources is very complex.

In addition, the flux of the nuclei of compact radio sources shows a rapid variability, of the order of a day or even an hour, from radio to optical wavelengths. An extrinsic origin to the source can be due to the phenomenon of scintillation, caused by the interstellar medium located on the line of sight between the radio source and the observer; however, this interpretation is only valid for radio variations. Optical variations suggest a change of intrinsic origin, caused by a phenomenon that occurs in the nucleus of the radio source; the explanation is a deformation of central parts of the accretion disk, which rotates at a speed of a few days and causes a small perturbation of the plasma ejection, responsible in turn for the variability of radio and optical emission of compact radio sources (Roland et al 2009).

3.1.6.2 Evolution of Radio Sources and Active Galactic Nuclei

The discovery of powerful radio galaxies that were already massive at extreme distances (redshifts larger than 6, that is less than 10% of the age of the Universe) raises the long-standing debate about how star formation is related to nuclear activity. Using adaptative optics, the discovery of young stellar populations associated to radio jets of AGNs favors such a link. Primeval galaxies would be triggered and formed as distant radio sources. As a consequence, the evolution of galaxy bulges, in which radio galaxies are embedded, is strongly constrained by such observations associating nuclear and stellar physics. Scientists of the group have devoted a large part of their activities to these theoretical and observational developments. As members of the international consortium "High Redshift Radio Galaxies" (HzRG), they participate in the creation of a catalogue of powerful distant radio sources observed in the optical and in the infrared with the instruments IRAC, IRS and MIPS of the Spitzer satellite (Seymour et al. 2008a, 2008b, 2007a). Moreover, submillimetric observations with Herschel (SPIRE and PACS instruments) are in the data processing phase while an ALMA proposal has been submitted. The evolutionary galaxy code PÉGaSE (http://www.iap.fr/pegase), with an improved dust emission in its last version (PÉGaSE.3, see Sect. 3.3.1), is used to measure stellar and nebular masses of the distant radio galaxy counterparts (Rocca-Volmerange et al. 2008, Seymour et al. 2007b), thus ensuring the coherence of the panchromatic view. In the HzRG consortium, PhD fellow Guillaume Drouart with supervisors at IAP and ESO is conducting research on the interpretation of the observations with APEX, VLT, Spitzer, Herschel, and ALMA (thesis started in October 2010, entitled "Evolution of Radio Galaxies in the Early Universe: Star Formation and AGNs").

A detailed low-frequency radio study on deep fields was launched with the Indian GMRT radiotelescope at 325 and 151 Mhz frequencies. This will be combined with far infrared data (Spitzer and Herschel), in order to analyze the cosmic star formation and its cosmological evolution. The first observations are done on the ELAIS N1 field (Sirothia, Dennefeld et al. 2009, 2010): they reveal a large number of steep spectrum radio sources that could be very distant. Their optical counterparts are searched while radio surveys are completed at lower frequency. In the X-ray domain, optical counterparts of AGNs detected in the XMM-LSS field (Tasse et al. 2008, 2010) were analyzed with the evolutionary galaxy code PÉGaSE (see Sect. 3.3.1).

3.2 Spectral and Morphological Properties of Galaxies

The "Origin and Evolution of Galaxies" group at IAP has internationally recognized expertise in the spectral modeling of galaxies and in the processing of astronomical images and the associated sources. Confronting models and observations can provide important constraints, for example on the history of star formation.

3.2.1 Galaxy Spectral Modeling

Analyzing the spectral energy distribution of a galaxy allows the derivation of consistent constraints on the stellar, gas and dust contents. Spectral synthesis codes can be used in this way to lift fundamental degeneracies affecting galaxy spectra and to extract valuable information from them. By studying galaxies at various cosmic epochs, one can constrain the evolution of their different constituents, and hence, better understand the formation of the galaxy population as a whole.

To improve the analysis of infrared data obtained by Spitzer and Herschel, we developed version 3 of the PÉGaSE code (http://www2.iap.fr/pegase) (Fioc et al., in prep.). The spectral energy distribution of a galaxy may be computed from the ultraviolet to the far infrared for a large variety of evolutionary scenarios, e.g. with several star formation, infall or outflow episodes; this should prove useful in cosmological simulations of galaxy formation. The user can now easily provide input parameters and obtain more detailed outputs, such as the spectrum of the various components contributing to the emission (see Figures 3.3 and 3.4 for a Milky Way-like galaxy). The chemical evolution of the major elements is also computed, and the radiative transfer code has been adapted to more realistic geometries. Two major improvements are in progress: the implementation of the library of high resolution stellar spectra of Munari et al. (2005) and the modeling of the nebular emission of H II regions at non-solar metallicities.

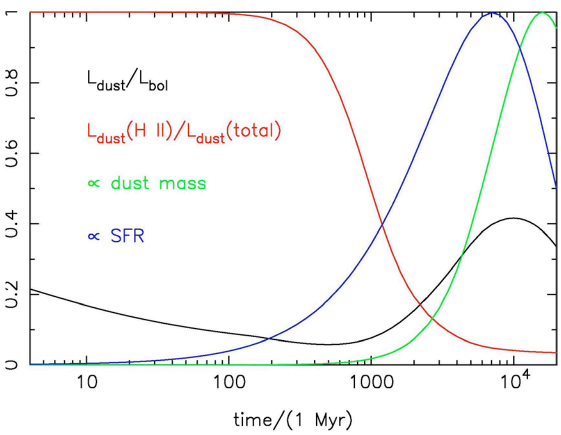


Figure 3.3. *Dust luminosity in an Sbc galaxy. Black: dust-to-bolometric luminosity ratio. Red: fraction of dust luminosity emitted by H ii regions. Green: dust mass. Dark blue: star formation rate.*

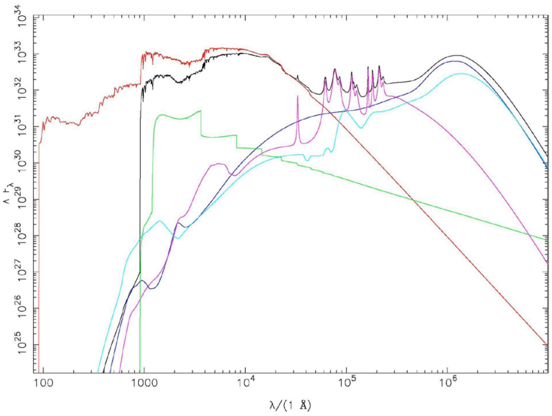


Figure 3.4. *Spectrum of an Sbc galaxy at 10 Gyr (black). Red: stellar emission (without dust). Green: nebular emission. Dark blue: graphites. Light blue: silicates. Purple: PAH.*

Other scientists of the group have developed a simple and largely empirical prescription to interpret the combined ultraviolet, optical and infrared emission from stars and dust consistently (Da Cunha et al. 2008). In this model, the infrared spectral energy distribution of a galaxy is computed as the sum of several dust components (PAHs, hot grains and grains in thermal equilibrium), both in stellar birth clouds and in the ambient interstellar medium, the latter also including a component of cold grains in thermal equilibrium. This model is both simple and versatile enough that it can be used to derive statistical constraints on the star formation histories and dust contents of large samples of galaxies using a wide range of ultraviolet, optical, and infrared observations (Da Cunha et al. 2010, Dunne et al. 2011; see Figure 3.5).

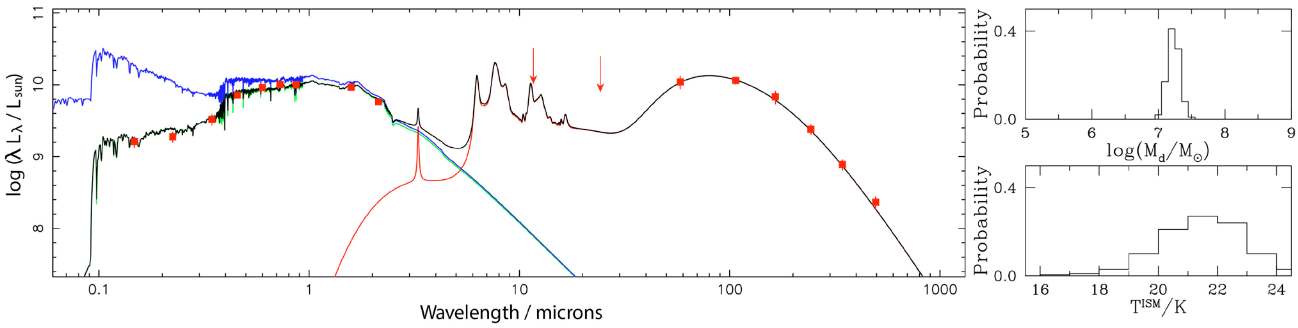


Figure 3.5. *Example of ultraviolet, optical and infrared spectral fit (left) and constraints on the total stellar mass and the diffuse dust temperature (right) of a galaxy from the SDSS optical survey observed with the GALEX (ultraviolet) and Herschel (infrared) satellites. In blue: un-attenuated stellar emission; in green: attenuated stellar emission; in red: dust emission; red squares with error bars: observations.*

In addition, new statistical tools for the spectral analysis of galaxies have been developed: these are based on sophisticated algorithms of spectral compression (Panter et al. 2007, 2008), principal component analyses of narrow spectral regions (Wild et al. 2007), and on the multi-wavelength analysis of individual pixels in optical and infrared galaxy images or spatially resolved galaxies (Zibetti et al. 2009). These methods allow original constraints on the hierarchical growth, stellar mass and star formation and chemical enrichment histories of galaxies (Panter et al. 2007, 2008, Arnouts et al. 2007, Salim et al. 2007, 2009, Eminian et al. 2008, Gallazzi et al. 2008, Wild et al. 2007, 2009, Walcher et al. 2008, Brinchmann et al. 2009, Lamareille et al. 2009), as well as on the link between black hole growth and star formation in galaxies (Kauffmann et al. 2007, Wild et al. 2010).

Finally, a new model has been developed to extend the spectral synthesis technique to the interpretation of galaxies with metal abundance ratios different from those in the solar neighborhood (Coelho et al. 2007). Through an approach of "differential" spectral synthesis, this model allows one to characterize the influence of changes in [Fe/H] and [α/Fe] abundance ratios on the determination of galaxy physical parameters (Walcher et al. 2009).

3.2.2 Spectral Library of Galaxies

The Gaia satellite will observe millions of unresolved galaxies for several years. The detection and classification processes are automatized with the help of the "Unresolved Galaxy Classifier" (UGC) software package based on Support Vector Machines (SVM), a supervised learning technique. The SVM training is done on the basis of a large spectral library of synthetic templates of galaxies, built with the evolutionary galaxy code PÉGaSE described above (Tsalmantza et al. 2007, 2008, 2009, 2011, Rocca-Volmerange et al. 2008, Livanou et al. 2010, Karampelas et al. 2010; see Figure 3.6). In its last version, the classification by type is optimized by a principal component analysis (Karampelas et al. 2011). The galaxy detection and the main specific parameters will be simultaneously derived in a second time.

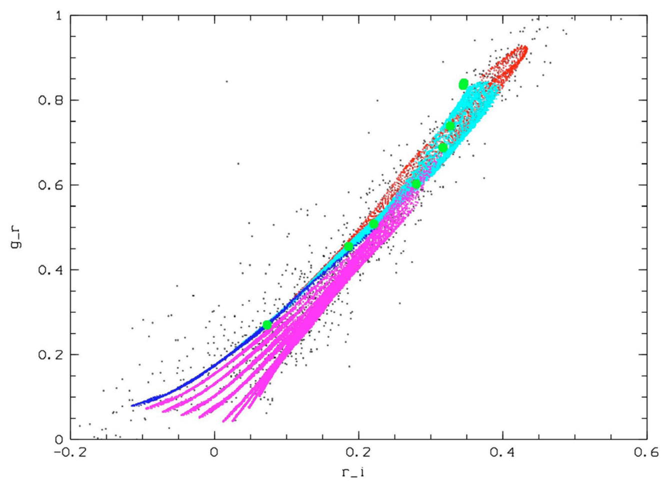


Figure 3.6. *The g-r/r-i color-color diagram from the SDSS catalog (dots) is fitted by the synthetic galaxy library from the code PÉGaSE (color lines), to prepare for the Gaia procedure of unresolved galaxy selection.*

3.2.3 Cosmic Star-Formation History

The Spitzer and Herschel space telescopes provide new accurate measurements of the star-formation activity taking place in optically-thick dust cocoons in nearby and distant galaxies. The “GOODS-Herschel” project, in which IAP is involved, allowed performing observations of the “Hubble Deep Field” North and South in the far infrared. These data, the deepest at these wavelengths for distant galaxies, revealed a puzzling uniformity of dust temperatures in galaxies across cosmic ages (Elbaz et al. 2010, Hwang et al. 2010). Measurements of the full infrared spectral energy distributions revealed an almost constant ratio between total infrared luminosity and the rest-frame 8 micron luminosity, which can therefore serve as a good proxy for the star formation rate. This ratio is slightly smaller for more compact and hotter starbursting galaxies. The redshifts and stellar masses of these galaxies were measured using the ZPEG code (Le Borgne and Rocca-Volmerange 2002).

In parallel, Le Borgne et al. (2009) modeled empirically the history of the cosmic star formation rate by simultaneously de-projecting galaxy counts at various wavelengths (see Figure 3.7). This non-parametric inversion led to an indirect measurement of the cosmic star-formation history with uncertainties. Several teams abroad have used this model in order to prepare and analyze observations of distant galaxies with Herschel. An independent parameterized inversion of galaxy counts (Bethermin et al. 2011) showed that the uncertainties estimated by the non-parametric inversion are realistic.

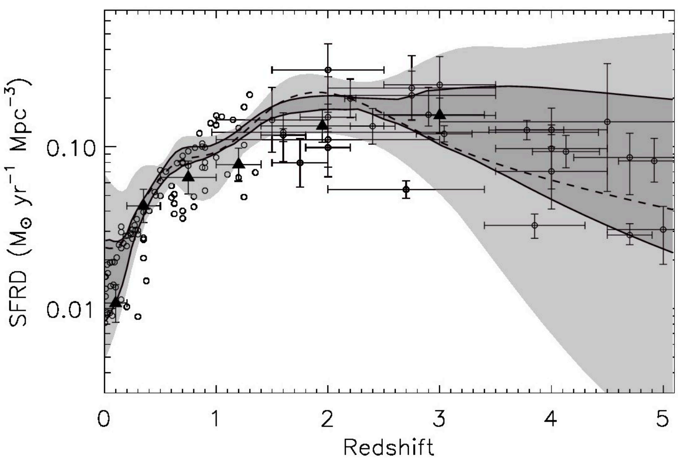


***Figure** 3.7. Evolution of the star formation rate density since redshift 5, modeled (gray areas) from a non-parametric inversion of infrared galaxy counts. The data points are independent observations using various diagnostics in the ultraviolet, optical and infrared.*

3.2.4 Image Analysis and Galaxy Morphology

If the spectral evolution of galaxies has been largely explored using photometry and spectroscopy, the evolution of morphology remains to be quantified precisely. The challenge lies in the instability of the available shape estimators because of their sensitivity to the image quality (noise, sampling, point spread function) and the impact of the selection effects (surface brightness). A large program of visual and automatic determination of galaxy morphometry from the existing extensive digital surveys has been undertaken by scientists in the group. This program is made possible by software developments in the analysis of astronomical images, and by the purchase of significant computing and storage capabilities.

3.2.4.1 A Visual and Automatic Morphological Catalog

A reference sample of 4458 nearby galaxies with ugriz imaging extracted from the "Sloan Digital Sky Survey" (SDSS) was built in the context of the EFIGI project ("Extraction de Formes Idéalisées de Galaxies en Imagerie"), and led to a PhD thesis (Baillard 2008). Detailed visual morphology of the 4458 galaxies was performed using 16 shape attributes (along 5 intensity levels and with a confidence interval); these attributes describe the different components of galaxies, their dynamical structure, their texture, their appearance on the sky, and their environment (Baillard et al. 2011). The goal is to relate the shape of a galaxy to the underlying physical phenomena, and to take into account the impact of the surroundings and of the observation biases on the apparent shape. This catalog (http://www.efigi.org) allows us to perform, for the first time, a detailed and quantitative description of the visual Hubble sequence (de Lapparent et al. 2011): the sequence is linked to the decrease of the bulge-to-total luminosity ratio, with nevertheless a five-type dispersion, as well as a progressive decrease of the arm winding; this result is confirmed by application of a supervised learning task for the Hubble type from the shape attributes (Baillard 2008).

The fitting of EFIGI galaxies with bulges and disk profiles convolved with the Point Spread Function (PSF) using SExtractor (see Sect. 3.2.4.2) points to some systematic biases in the SDSS data reduction pipeline: flux underestimation for bright galaxies, as large as 2 magnitudes, due to an insufficient area for sky background estimation; shredding of late spiral and irregular galaxies, hence an underestimation of their fluxes; a contamination of distant objects by halos of bright stars, and the presence of ghost sources. The new profile fits performed by SExtractor also show a progressive shift in color along the morphological sequence, with no dichotomy between red and blue galaxies. In contrast, the separation of bulges and disks indicates that the former are red, and the latter describe the full color interval down to the blue colors of irregular galaxies (de Lapparent, Bertin, in prep.; see Figure 3.8); this contradicts the existing results, which might be affected by biases in the profile fits (Peletier and Balcells 1996; Cameron et al. 2009).

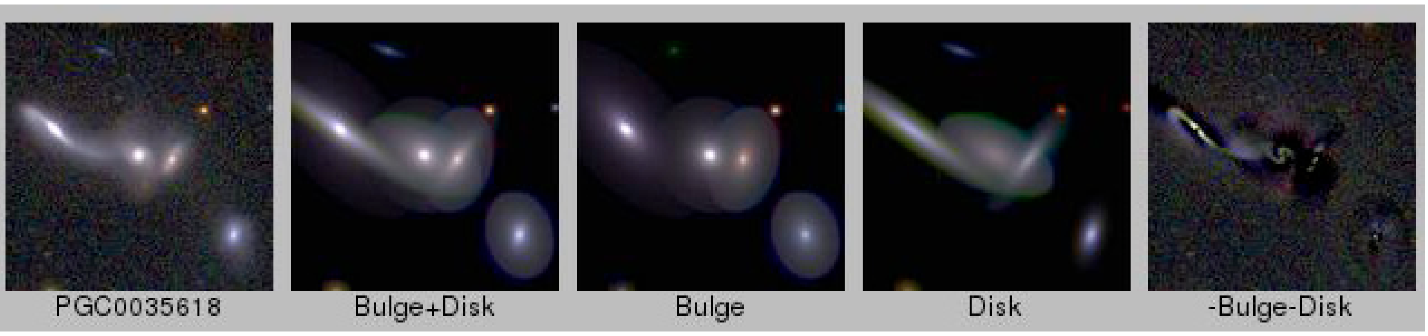


Figure 3.8. *SExtractor modeling of the central galaxy PGC0035618 and its neighbors by the sum of a bulge with a de Vaucouleurs profile and an exponential disk. From left to right: SDSS image in the EFIGI catalog, sum of bulges and disks, only bulges, only disks, and residuals from the bulge plus disk models.*

Besides, a new type of compact dwarf galaxy has been discovered by Chilingarian & Mamon (2008), with structural properties intermediate between compact ellipticals and ultra-compact dwarfs. Located at the outskirts of the giant elliptical M59 in the Virgo cluster, this dwarf has an age and metallicity suggesting that it originates from a much more massive dwarf elliptical that lost 90% of its stars, stripped by the tides of M59.

3.2.4.2 Software for Image Analysis

Software developments around the SExtractor open source photometry package have been carried out further and a new dedicated website, AstrOmatic.net, has been put online. The AstrOmatic website hosts various maintenance activities dedicated to the ten software packages that have been released to the community so far. AstrOmatic packages were registered by the CNRS "Partnership and Enhanced Value" division (SPV) at the French software protection agency (APP) in 2010, allowing a support contract to be signed between CNRS and the Excellence Cluster in Germany and the Fermi Consortium Alliance (USA).

Reliable models of sources, of the noise, and of the PSF are required to allow one to describe the content of astronomical images with good accuracy. The PSFEx package, which went officially public in 2010, makes it now possible to model the PSF and its variations in a fully automated way (Bertin 2010b). The software had been used for years as a prototype, mostly for automated image quality assessment in imaging pipelines (AstroWISE, TERAPIX), as well as stellar astrometry and photometry (Bouvier et al. 2008, Delorme et al. 2008, 2010, Bertin 2011a). PSFex is now a key ingredient of multi-component galaxy modeling procedures (Bertin 2011) which are being applied by research group members to Canada-France Legacy Survey (CFHTLS) images. PSFEx also includes an experimental module for homogenizing PSFs across images; this development was carried out in collaboration with Dark Energy Survey team members (Mohr et al. 2008, Darnell et al. 2009), and has been applied for the first time to the Blanco Cosmology Survey (e.g., High et al. 2010, Zentano et al. 2011).

3.3 Matter Distribution in Galaxies, Groups and Clusters

The scientists of the "Origin and Evolution of Galaxies" group at IAP set out to observe and characterize the matter distribution at large scales, from individual galaxies to bound or relaxed structures such as groups and clusters. The latter are the main sites of galaxy transformations. Observations, together with numerical and analytical simulations, allow one to link the baryonic matter in and around galaxies with the underlying dark matter halos.

3.3.1 Structure of Groups and Clusters of Galaxies

Two recent studies have clarified the ongoing debate on the nature of compact groups of galaxies (CGs): the analysis of redshift-independent distance measures of galaxies in the Virgo cluster (Mei et al. 2007) shows that the closest CG (around M60 in Virgo) is caused by the chance alignment of two pairs of galaxies, separated by at least 600 kpc along the line of sight (Mamon 2008). Moreover, an analysis of three mock galaxy catalogs, derived from three different semi-analytical models applied to the Millennium simulation of the cosmological evolution of dark matter, indicates that 2/3 to 3/4 of mock CGs, selected in the standard observed fashion, are physically dense in 3D, while the remaining 1/4 to 1/3 is caused by chance alignments of galaxies within virialized groups (Díaz-Giménez & Mamon 2010).

One member of the team has been part of a large collaboration on the Coma cluster (Adami et al. 2007a, 2007b, 2007c, 2008a, 2008b, 2009a, 2009b, 2009c). Clusters were found to be still forming, and showing evidence for mergers (Durret et Lima Neto 2008). The analysis of pairs of clusters (Durret et al. 2010, 2011) has confirmed that mergers cause inhomogeneities in the temperatures and metallicities of the hot gas (see Figure 3.9). They can also create dips and wiggles in galaxy luminosity functions. Mergers can increase the star formation rate, as in the filaments falling onto Abell 85 (Boué et al. 2008), or in the one joining Abell 1763 and 1770 (Biviano et al. 2011).

The analysis and modeling of the physical mechanisms at play in clusters of galaxies show the importance of non-thermal phenomena (Prokhorov 2008, Prokhorov et al. 2009, Prokhorov 2010). A viscous force has an effect on the gas of a small cluster crossing a larger one (Prokhorov and Durret 2007), and the gas metallicity implies a non-maxwellian electron distribution (Prokhorov 2009; also see Durret et al. 2008, for a contribution to a book on non-thermal phenomena in clusters). Moreover, the study of superclusters has shown that filamentary structures were richer, larger and more luminous than pancake structures (Costa-Duarte et al. 2011).

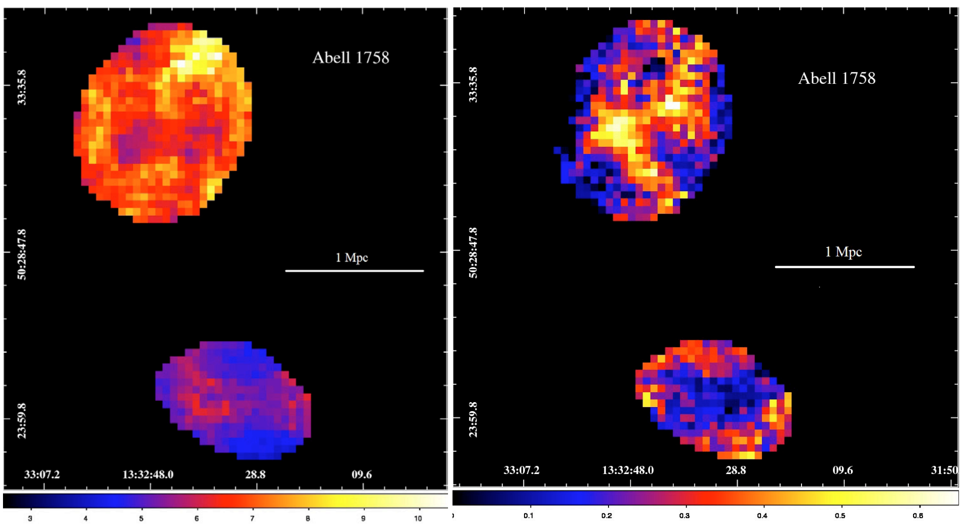


__Figure 3.9.__ Maps of temperature (left) and metallicity (right) of the X-ray gas in the pair of clusters Abell 1758 North and South obtained with the MOS1, MOS2 and pn instruments of the XMM-Newton satellite.

3.3.2 Modeling the Mass and Velocity Anisotropy Profiles of Galaxies and Clusters

The analysis of the radial profiles of the density profiles of dark matter in elliptical galaxies, groups and clusters is subject to a degeneracy between the radial profiles of total mass and velocity anisotropy (linked to the orbital shapes). This degeneracy was partially lifted by the first algorithm of mass inversion of spherical structures of known anisotropy (Mamon & Boue 2010, Wolf et al. 2010). Moreover, the 6D distribution function of ΛCDM halos in cosmological simulations has recently been parameterized in simple form in terms of energy and angular momentum (Wojtak et al. 2008). This allows the measurement of mass and anisotropy profiles from observations (Wojtak et al. 2009).

3.3.3 Influence of Environment and Mass Accumulation in Galaxies

The role of environment in the history of galaxies has been explored in various ways. Carlberg et al. (2009) extended the measurements of the angular correlation function for small mass galaxies in the CFHTLS. Hwang et al. (2011) established a link between galaxy merging and star-formation in infrared galaxies seen by Herschel. In the cosmological numerical simulation "MareNostrum," managed at IAP, Gay et al. (2010) showed that galaxy colors are better correlated to the distance from the halo centers than to the distance from filaments. Finally, Devriendt et al. (2010) proposed a model for the luminosity function of galaxies observed in the ultraviolet at large redshifts, based on a hierarchical formation scenario in a ΛCDM universe.

Cattaneo et al. (2011) have developed an innovative approach to galaxy formation, where the mass formed in stars after gas accretion onto the disk is a simple, one-equation function of time and of the mass of the galaxy dark halo; mergers are controlled in a very high resolution, cosmological simulation without gas. Their model suggests that the mass growth of galaxies depends on the final mass in stars: dry major mergers dominate the growth of massive galaxies with Mstars > 1011 Msun, while gas accretion dominates below this mass (even for dwarf ellipticals); moreover, galaxies lose typically 40% of their stars by tides at each orbit, as independently found by Klimentowski et al. (2009) with simulations of pairs of galaxies of very unequal mass.

Indeed, the properties of galaxies depend not only on the mass of their stellar component, but also on their environment, especially the projected distance of the galaxy to its host group/cluster. It turns out that this radial segregation of galaxy properties is modulated by the line-of-sight velocity of the galaxy relative to its host (Mamon et al. 2010), which allows the deprojection of the fraction of galaxies with recent starbursts (Mahajan et al. 2011).

3.4 Outlook

In the future, the scientists in the "Origin and Evolution of Galaxies" group at IAP will continue to use the data provided by the large ground-based surveys in the visible (SDSS, 6dFGS, CFHTLS) and the near infrared (WIRDS, UKIDSS), and those that will be obtained in with the VST and VISTA at ESO, Pan-STARRS and the "Dark Energy Survey," which will bring an improvement in sensitivity, angular or time resolution. Multi-wavelength follow-up campaign will be organized, with available space observatories, XMM, Chandra, HST and later NIRSPEC on the JWST, and submillimeter and radio observations with ALMA and LOFAR.

The main impact of Gaia will be a detailed study of the structure of the Milky Way, making our Galaxy a benchmark for the study of other galactic disks. Our team will contribute to the GAIA science in several directions.

A new model with a self-consistent scenario describing the various properties of the Milky Way in a cosmological framework, with enough spatial resolution to describe key physical processes (star formation, feedback etc.) is being developed at IAP in collaboration with scientists from the "Laboratoire d'Astrophysique de Marseille". A parallel effort concerns the development of a new generation of semi-analytical models, including in particular the radial migration of stars in the disk under the action of the spiral arms and the bar, an effect largely ignored up to now.

The Gaia library of synthetic galaxy spectra will be extended to higher redshift and with improved spectral resolution, by taking into account new sources, the nebular emission and the effects of cosmology and evolution.

Moreover, about 6000 Supernovae will be observed with the Gaia satellite over its five-year lifetime; among them, about one third will be detected before their maximum. These will provide an unprecedented sample. A consortium of small telescopes located in both hemispheres is being organized to obtain the optical spectroscopy of the detected variable sources.

Data from the Gaia satellite will also have multiple cosmological applications, among which the estimation of flattening of the dark matter halo and the detection of dark clumps of less than 108 solar masses. Moreover, Gaia will provide a new tool to derive astrometry measurements of binary systems of supermassive black holes, whose characteristics (size and positions) will be measured and compared to the results obtained by VLBI.

In parallel, the link between the physics of local galaxies and of the distant galaxies will be thoroughly improved using HST, Herschel, ground-based radio observations, completed by new modelling including hydrodynamics. Integral spectroscopy of starburst galaxies is planned with the aim to measure the impact of Wolf-Rayet and massive stars onto the interstellar medium. The evolution of the interstellar composition will be explored owing to the large sensibility and stability of the COS spectrograph. It will be possible to measure abundances from non-saturated lines in the HI phase. Finally, a large project is aimed at characterizing host galaxies of SNe for a significant subsample of the SDSS using images from which morphologies can be determined. The new results from the key-programs obtained by Herschel in far infrared, as well as the full sky survey with Planck at millimeter wavelengths will allow the scientists in the group to better understand the processes of star formation and the relationship with active nuclei, and their impact on the ultra-deep galaxy counts and the extragalactic background diffuse emissions.

The analysis of the observations made by Spitzer and Herschel calls for improved galaxy spectral synthesis and evolution codes. Radiative transfer must be computed consistently in star forming regions, especially to reliably determine the fraction of escaping or absorbed Lya photons; the multi phase structure around young stars should be better taken into account; and the production destruction cycle of the dust should be modelled in a less phenomenological way; finally, the high spatial resolution now available in the whole range of the infrared emphasizes opens the possibility to model the different components of a galaxy rather than using only integrated properties.

The required data for the development of the latter models will be obtained by the compared morphometric analysis of the nearby galaxies in the SDSS and the distant galaxies in the CFHT "Legacy Survey" fields. By new spectrophotometric scenarios applied to the bulge and disk components of the various galaxy types, the goal is to constrain the history of star formation, and the impact of major mergers onto the Hubble sequence. A better understanding of the transformation of galaxies of different types and the effects of the environment will involve the study of their clustering within the group and cluster environments. A new Bayesian algorithm is being developed that will optimally define these environments from redshift space samples, and will be calibrated on cosmological simulations. Moreover, realistic prescriptions for the physics of the environment, based on dynamical and hydrodynamic simulations, will be incorporated in the models of galaxy formation.

An important step in the modeling the spectrophotometric evolution of galaxies is the use of numerical simulations over large cosmological volumes for calibrating the evolving scenarios by galaxy type, and for studying the influence of feedback and of the environment on the onset and suppression of star formation. These simulations will be used to explore the spectral synthesis of active galaxy nuclei and their relationship with primordial galaxies at high redshift, and to deduce the importance of these objects for future observations with ALMA. These improvements in the modeling of the spectrophotometric evolution of galaxies will be crucial for interpreting the numerous emission-line galaxies, HII or AGN, for which spectroscopy will be obtained with the Euclid satellite. The knowledge of the interstellar medium of nearby galaxies will be instrumental for defining searches for distant galaxies and active nuclei from the Euclid observations. The scientists in the group will detain the tools for modeling both the angular profiles and the spectral energy distributions of the millions of galaxies detected by imaging and spectroscopy with Euclid, thus for quantifying the selection effects of slitless spectroscopy in the near infrared, and for improving the techniques of photometric redshifts.

In order to explore the processes taking place in the evolution of groups of galaxies, and to compare them with those at play in clusters, one has to evaluate the role of the different baryonic components in groups: diffuse and galactic stellar matter, and hot gas. The analysis of a large sample of galaxy groups has been undertaken, based on SDSS, CFHT/Megacam and XMM-Newton data. In parallel, the properties of the 91 distant and massive clusters of the DAFT/FADA survey are being analysed in order to better constrain the physics of distant clusters, and to derive cosmological constraints through weak lensing tomography. Moreover, the thousands of galaxy clusters detected in the CFHT "Legacy Survey" fields provide scientists with an unprecedented sample of distant clusters, whose dynamics will be studied thanks to the VIPERS spectroscopic survey (ESO "Large Program," covering the redshift interval z~0.5-1.2), as well as the effects of environments in relation with the morphometric analysis.

Cosmology & High-Energy Astrophysics

4

The research group "Cosmology and High-Energy Astrophysics" (COSMOH) consists of:

3 CNRS researchers: Robert Mochkovitch, Pasquier Noterdaeme (recruited in 2010), Marta Volonteri (recruited in 2011)

4 CNRS emeritus researchers: Jean Audouze, Jacqueline Bergeron, Jean-Pierre Lasota, Alain Omont

1 CNRS research engineer: Elisabeth Vangioni

3 UPMC assistant professors and professors: Patrick Boissé, Frédéric Daigne, Emmanuel Rollinde

1 astronomer: Patrick Petitjean

1 Professor UPMC/ERC: Joe Silk

During the period 2007-2011:

9 post-doctoral researchers: Daniel Albornoz Vasquez, Alexander Belikov, Željka Bošnjak, Hum Chand, Andrew Fox, Maria Polletta, Ramia Sethuram, Lucas Z. Uhm, Gilles Vertongen

11 PhD students: Ali Reza Aghae, Sara Caucci, Andrej Dobrotka (co-supervision), Nicolas Fiolet, Franck Genet, Pasquier Noterdaeme, Yu Pei, Romain Hascoët, Isabelle Pâris, Susanna Vergani (co-supervision)

7 PhD thesis were defended: Ali Reza Aghaee, Sara Caucci, Nicolas Fiolet, Franck Genet, Pasquier Noterdaeme, Isabelle Pâris, Hannachi Zitouni

2 "habilitations à diriger les recherches" were also defended: Frédéric Daigne and Emmanuel Rollinde

HDR: 11

Publications: I: 242, II: 77

The research activities of the group COSMOH are focused on the study of various astrophysical high- energy sources, and on the use of these sources as tracers of the cosmic history. Our ambitious theoretical and observational program follows four main axes:

- Models of high-energy sources. They are usually associated to accreting compact objects with (sometimes relativistic) ejections. We want to identify the common physical mechanisms shared by these sources. Taking advantage of new instruments (Swift, 2004; Fermi, 2008), we focus on gamma-ray bursts (GRBs) and develop an original approach to model all the emission phases (prompt, afterglow) at all wavelengths and build a consistent physical picture of these phenomena.
- Big Bang Nucleosynthesis (BBN) and cosmic history of baryons. Our understanding of the BBN has now reached a level that allows us testing primordial cosmology models implying new physics; this includes the study of possible variations of fundamental constants. Besides, the BBN determines the initial composition of the Universe for the cosmic evolution of baryons. We build a consistent model of this evolution from the end of the dark ages to the present epoch, in the framework of hierarchical structure formation. We focus on the characterization of the first stars, on the reionization, and on the chemical evolution in the intergalactic (IGM) and interstellar medium (ISM).
- Detection and characterization of high redshift sources. We use several large surveys from the optical to the sub-millimeter range to detect distant supermassive objects, galaxies and quasars. Sub-millimeter studies allow characterizing individual sources (star formation, molecular content, etc.) and providing observational constraints for cosmic evolution models. Due to their randomness and short durations, GRBs need a specific strategy: COSMOH is involved in the SVOM project (chapter 7.3.5).
- Spectral probe of the ISM & IGM. Absorption lines in quasar and GRB spectra are due to the ISM of the host galaxy or of intervening structures along the line of sight, and to the IGM. The spectral analysis allows us characterizing the properties of the absorbing gas and its distribution in the radial direction, and in the transverse direction by using several lines of sight, and studying the evolution of the IGM, and of the ISM and environment of galaxies. We probe the local ISM similarly with stellar sources. Therefore, spectroscopy is a powerful tool to probe low density regions (IGM), as well as forming structures (damped Lyman-a systems) and the ISM of collapsed structures. The precision with VLT/UVES is such that even the variation of physical constants between the Universe at z~2 and the present epoch can be tested to constraint fundamental physics.

These four axes are strongly connected, GRBs and quasars playing a central role. We aim at (i) detecting them, characterizing their populations, measuring their properties; (ii) identifying the physical mechanisms at work; (iii) detecting them at high redshift, probing the physical conditions at different epochs in different sites; (iv) modeling the cosmic evolution of baryons. Massive stars are also key ingredients in this program: they drive the chemical evolution (stellar nucleosynthesis), but are also the progenitors of explosions (supernovae and GRBs), which power galactic winds (IGM enrichment) and the acceleration of cosmic rays (spallative nucleosynthesis). The first generation of massive stars, which might be directly probed with GRBs, triggers the transition at the end of the dark ages, as a source of ionizing photons and of early chemical enrichment.

COSMOH is involved in two projects at the frontier between high energy astrophysics and cosmology: (i) SDSS-III/BOSS (chapter 7.2.6) which maps the distribution of quasars and galaxies to study the characteristic distance scale imprinted by baryon acoustic oscillations (BAOs) in the early Universe. This measure puts important constraints on the nature of dark energy, a major issue in cosmology since the discovery of the accelerating Universe; (ii) SVOM (chapter 7.3.5) to observe GRBs and their afterglows, understand the physical processes at work, and use their huge luminosity for cosmology.

From 2007 to 2011, researchers from COSMOH have initiated or contributed to three ANR projects: (i) JETS_GAMMA on the high-energy emission from relativistic jets (01/2006 – 09/2009), (ii) BOSS on BAOs (01/2009 – 12/2012), (iii) VACOUL on the variations of fundamental constants (09/2011- 12/2015). These projects imply researchers from IAP and other INSU or IN2P3 institutes (IPAG, LRR, LPTA, APC, IRFU, CSNSM). With the list of our collaborators and visitors, it shows that our activities are carried out in a French and international environment with a large interdisciplinary component (interactions with nuclear, fundamental and particle physics). We list below our activities and main results from 2007 to 2011.

4.1 Models of Astrophysical High-Energy Sources

4.1.1 Galactic Compact Sources, Intermediate Mass and Supermassive Black Holes

4.1.1.1 Supermassive Black Holes (SMBHs) in Galactic Centers: Ejection Mechanism–Evolution

We have discussed the respective role of the accretion and the black hole spin for the ejection by SMBHs in Active Galactic Nuclei (AGNs) (Sikora, Stawarz & Lasota 2007). We find in a radio intensity versus accretion luminosity diagram that all sources show the same tendency but are distributed in two separated sequences: at a given accretion luminosity, AGNs in giant elliptical galaxies are about 103 brighter in radio than in disk galaxies. A natural explanation is the role of the black hole rotation, which may be higher for SMBHs in elliptical galaxies. This favors the Blandford-Znajek mechanism where the rotational energy is extracted via magnetic field lines anchored in the ergosphere. This work is related to SMBH evolution studies (Volonteri, Sikora & Lasota 2007). We find that higher spins are found in elliptical galaxies in galaxy formation scenarios where the SMBH is growing by the accretion induced by successive mergers, whereas the growing in spiral galaxies is related to brief, weak but frequent accretion episodes, such as the accretion of a star.

4.1.1.2 Intermediate Mass Black Holes (IMBHs): the Hyper-Luminous X-ray Source HLX-1

HLX-1 in the spiral galaxy ESO 243-49 is most certainly an IMBH as the peak luminosity reaches 10^4 times the Eddington luminosity of one solar mass. Different methods converge towards a mass between 10^3 and 10^4 $M_{\odot}$. The light curve is variable, with a possible recurrence on a 380 days timescale. Outbursts have a shape and spectral evolution with several features similar to those observed in transient low mass X-ray binaries with a stellar mass black hole. However, we have shown that the same outburst mechanism cannot be at work in HLX-1 (Lasota et al. 2011). Therefore, the most probable origin of the variability seems to be a star on a very eccentric orbit coming close to the black hole. Multi-wavelength observations are necessary to test this scenario. We have obtained observing time at VLT and Gemini for this purpose (co-PI: J.-P. Lasota).

4.1.1.3 Astrophysical Black Holes: Accretion – Measurement of the Spin

Astrophysical black holes (Lasota 2007) are probed mainly via the accretion process and are described by only two parameters, the mass, deduced from the motions observed in the vicinity of the black hole, and the spin, which is determined by the spectral analysis of the radiation from the accretion flow. This necessitates relativistic models of accretion disks. We have developed such models beyond the thin disk approximation which is not valid anymore for high accretion luminosities, and have applied these models to measure black hole spins (Sadowski et al. 2011a,b; Abramowicz et al. 2010).

4.1.1.4 Evolution of Close Binaries Including a Black Hole

The agreement between the predictions of our model for the evolution of X-ray binaries including a black hole and observations (Yungelson & Lasota, 2008) leads now to study how the main assumptions – lack of magnetic braking of the orbital rotation at long periods and high ejection efficiency in the common envelope phase – can be explained by evolution models of close binaries.

4.1.1.5 Accretion: Dwarf Nova Outbursts and Neutron Star X-ray Bursts

The thermal-viscous disk instability model (DIM) has been developed to explain dwarf novae outbursts. We have constructed the first spectral model of a complete outburst cycle (Idan et al. 2010), which offers unique diagnostics for the accretion flow in close binaries. The DIM has also been proposed in other astrophysical sources. We show that it cannot explain the quasar luminosity function (Hameury, Viallet & Lasota, 2009) but that it can be applied to the helium disk of AM CVn stars, which allows a unique test of the DIM (Kotko, Lasota & Dubus 2010). Finally, the most critical issue is found in the initial context of the DIM: the distance of the well studied very bright dwarf nova SS Cyg has been recently revised. If GAIA confirmed this, it would lead to such an increase of the luminosity of SS Cyg that it may become impossible to reproduce it (Schreiber & Lasota 2007).

The modeling of X-ray bursts – thermonuclear explosions on the surface of neutron stars – allows measuring some properties, like the radius, and constraining the structure of these stars. It is crucial to understand how the nuclear fuel is accreted for the explosion. We find an unexpected link between X-ray bursts and the DIM developed for dwarf nova outbursts (Kuulkers, in't Zand & Lasota, 2009).

4.1.2 Gamma-ray Bursts and their Afterglows

Our research activities aim at developing a consistent description of all the emission phases observed in GRBs and their afterglows. The general scenario considers the formation of a new compact source (stellar mass black hole) and the production of an ultra-relativistic outflow. During the following evolution, shock waves form and propagate within the ejecta, due to its initial variability (internal shocks), or to the deceleration by the external medium (reverse shock). This deceleration also leads to a strong ultra-relativistic shock in the circumburst medium. In these various shocked regions, the dissipated energy can be radiated more or less efficiently and contribute to the observed emission.

Prompt GRB emission studies have recently benefited from a substantial improvement of the traditional spectral range (keV-MeV), in the optical with robotic telescopes triggered by GRB alerts generated by Swift, and in high-energy γ-rays (100 MeV-10 GeV) thanks to Fermi. We had already developed a full model of the dynamics of the ejecta. During the ANR project JETS_GAMMA (2007-2009; P.I. F. Daigne), we have coupled this model to a detailed radiative calculation, in collaboration with G. Dubus (IPAG, Grenoble). Such tools are well suited for the physical interpretation of recent observations. Studies with researchers from INTEGRAL (D. Götz, CEA/IRFU/SAp) and Fermi (F. Piron, LPTA, Montpellier ; S. Guiriec, MSFC, Huntsville, USA) have started. We have also joined in 2009 the GDRE "Exploring the dawn of the Universe with GRBs" which includes researchers from 11 institutes in Europe and aims at developing collaborations around the SVOM project (see 7.3.5).

4.1.2.1 The Origin of the Prompt Gamma-Ray Emission

We show that the predictions from the internal shock model are in good agreement with Fermi observations, which favor a radiation dominated by the synchrotron process, with a subdominant high energy component associated to inverse Compton scatterings in the Klein-Nishina regime (Bošnjak, Daigne &

Dubus 2009; Guiriec et al. 2010; Daigne, Bošnjak & Dubus 2011). Several correlations are observed between GRB temporal and spectral properties (Bošnjak et al. 2008; Firmani et al. 2009). We show that all these relations are equivalent and due to the same intrinsic spectral evolution (Hafizi & Mochkovitch 2007; Boçi, Hafizi & Mochkovitch 2010) which is reproduced qualitatively by internal shocks with a dominant synchrotron. A more detailed study of the quantitative predictions is in progress (Bošnjak et al. in preparation) and allows to put constrains on the efficiency of acceleration in relativistic shocks. The observed diversity of the GRB population is also reproduced, from the under-luminous GRBs to the brightest events (Daigne & Mochkovitch 2007; Zitouni et al. 2008).

4.1.2.2 The Lorentz Factor of the Relativistic Outflow

Our model allows constraining the physical conditions in the outflow. In particular, the lack of spectral cutoff at high energy implies a large Lorentz factor (>100) to beam the photons and avoid γγ annihilation. Our detailed calculation (figure 4.1) predicts lower limits for the Lorentz factor that are three times lower compared to the values obtained by the Fermi collaboration using a simplified approach (Hascoët et al. 2011a). This loosens the constraints on the physics of the central engine.

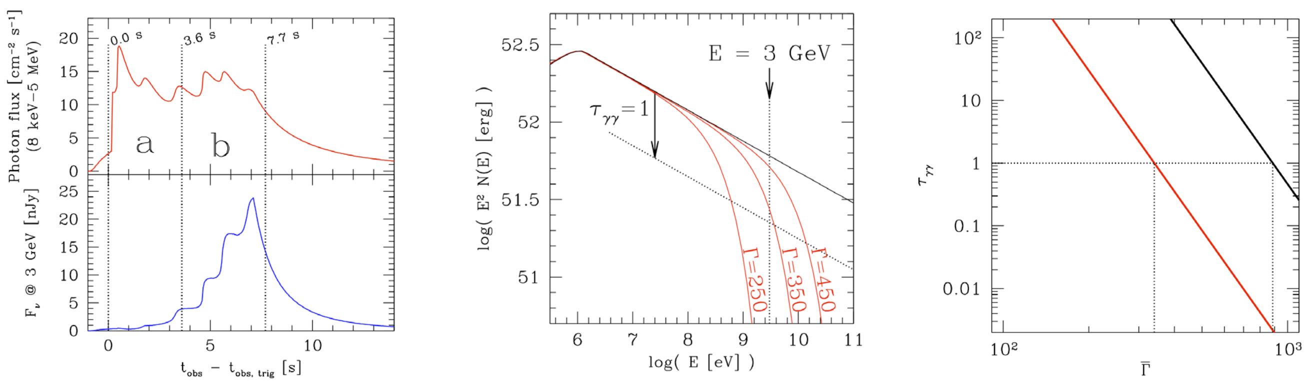


__Figure 4.1.__ GRB high-energy emission and constraints on the Lorentz factor in the outflow. We present a model of time bins 'a' and 'b' in GRB 080916C.
Left: γ-ray light curve at low (red) and high (blue) energy. In agreement with Fermi observations, the model reproduces the short timescale variability at low energy and the delayed onset of the GeV emission.
Middle: spectrum for different values of the Lorentz factor (red). The high-energy cutoff is due to γγ annihilation. The unabsorbed spectrum is plotted in black.
Right: γγ opacity at 3 GeV (maximum detected energy) as a function of the Lorentz factor (blue: our study; red: Fermi collaboration).

4.1.2.3 GRB Prompt Optical Emission

In the same theoretical framework, we show that the GRB prompt optical emission can be reproduced not only in standard cases with a moderate optical flux, such as GRB 041219A (Götz et al. 2011), but also in extreme cases such as the very bright "naked eye burst" GRB 0801319B (Hascoët et al. 2011d). The brightest case is associated to highly variable outflows with several generations of internal shocks.

4.1.2.4 Composition of the Relativistic Jet – Acceleration Mechanism

In addition to the non-thermal emission from internal shocks, a photospheric thermal emission is expected, which is associated to the release of the residual internal energy of the jet at the end of the acceleration phase. We predicted that this thermal component should usually be weak (Daigne & Mochkovitch, 2002, MNRAS, 336, 1271). This has possibly been confirmed by the observations of GRB 100724B by Fermi (Guiriec et al. 2011). Ghirlanda et al. 2007 have however shown that the photospheric emission may be dominant in some time intervals in some GRBs. We plan to develop a detailed model including both the thermal and non-thermal emission mechanisms. The comparison of the two components can constrain the jet magnetization, which is still poorly known despite a possible detection of γ-ray polarization in GRB 041219A by INTEGRAL (Götz et al. 2009). Such constraints would be of great importance to understand how relativistic outflows are accelerated.

4.1.2.5 The Physical Origin of the Afterglow

The afterglow is usually associated to the ultra-relativistic forward shock propagating in the external medium. However, this model does not reproduce well Swift observations that exhibit an unexpected variability. We have proposed that the reverse shock also associated to the jet deceleration but propagating within the outflow itself, may be the dominant source of the afterglow emission (Genet, Daigne & Mochkovitch, 2007). A large variability becomes possible. In collaboration with colleagues at Columbia University who have independently developed a similar idea, we have built a detailed model to compute the reverse shock emission (Genet, Daigne & Mochkovitch 2007; Uhm 2011; Beloborodov et al. 2011). We have now started an ambitious program to compare the standard model and our long-lived reverse shock model to available data. We test how both models can reproduce generic features such as X-ray flares and plateaus (work in progress), but also peculiar GRBs with an exceptional behavior, such as GRB 050820a (Genet, Daigne & Mochkovitch 2007), GRB 050421 (Hascoët et al. 2011b) or GRB 080503 (Hascoët et al. 2011c). Our first results show that the reverse shock model has a good capacity to reproduce observations, with parameters that are less extreme than for the standard model, and in better agreement with our knowledge of GRB progenitors. The model indeed favors a stellar wind density profile in the external medium, as expected for massive stars

4.2 Primordial Cosmology and Big Bang Nucleosynthesis

Since the measurement of the baryon density Ω_b from CMB anisotropies by WMAP, the BBN (Figure 4.2) has no free parameter anymore (Coc & Vangioni

2010). The main issue remains the discrepancy between the ^{7}Li abundance predicted by the BBN and the observed value in old halo stars. Nevertheless, the BBN is now well understood and can be used to constrain the new physics invoked in primordial cosmology. The impact of QCD on the nuclear physics at work makes the BBN predictions sensitive to different fundamental parameters: the gravitational constant, the three gauge coupling parameters and the Yukawa constants of the electron and the quarks. It offers a test for unification models, where these parameters, usually taken as constant, can now vary in a constrained inter-dependent manner. Our activities focus both on standard BBN and on tests of new physics.

4.2.1 Standard BBN up to CNO – the Problem of Lithium ^{7}Li

An experiment at the GSI synchrotron (Helmholtzzentrum für Schwerionenforschung, Germany) to measure the cross-section for the reaction ^{2}H(α,γ)^{6}Li – the main channel for the production of ^{6}Li – has allowed us to compute the primordial value ^{6}Li/H = 10^{-14} (Hammache et al. 2010). More generally, we have updated the BBN network in collaboration with nuclear and astro-physicists (A. Coc, CSNSM, Orsay; S. Goriely, ULB, Belgium). We have carried a complete calculation of the primordial abundances of all isotopes up to CNO using this up-to-date network with more than 400 nuclear reactions (Coc et al. 2011). This determines the initial conditions for the cosmic chemical evolution.

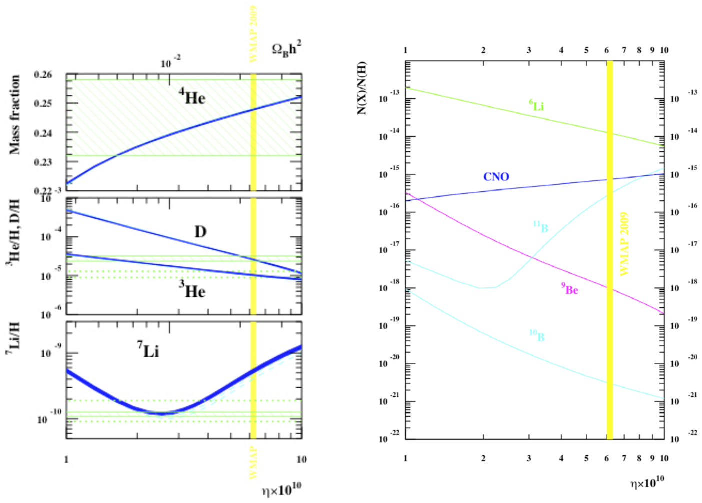


Figure 4.2. *Standard BBN. The abundances are plotted as a function of the baryon over photon ratio η or the baryon density $\Omega_b h^2$, whose measured value by WMAP is indicated by a yellow vertical line.*
Left: ^{4}He, D, ^{3}He, and ^{7}Li. The theoretical uncertainties are obtained by Monte Carlo (blue) and the green horizontal bands indicate the observations in different primitive astrophysical sites.
Right: ^{6}Li, ^{9}Be, ^{10}B, ^{11}B and CNO.

To reconcile ^{7}Li observations with BBN, we have studied the effect of the disintegration of unstable particles on the production/destruction of primordial elements. This constrains the parameter space of supersymmetric theories including dark matter made of neutralinos or gravitinos (Coc et al, 2011a, b).

4.2.2 Primordial Cosmology and Variation of Fundamental Constants

The BBN is highly sensitive to the balance between the gravitation and the weak interaction. The present precision allows testing alternative models of gravity. We show that the BBN is more constraining than other tests made in the solar system for at least two classes of models where the equivalence principle between ordinary and dark matter is violated (Coc et al. 2009).

We have studied the impact on the BBN of possible variations of fundamental parameters taking into account the predicted inter-dependence in unified theories (Coc et al. 2007). The variation of the binding energy of D can reconcile the predicted abundance of ^{7}Li with the observed value in old halo stars, without affecting the D and ^{4}He abundances, which already agree with observations.

4.2.3 Observational Constraints on the Variation of Fundamental Constants

Absorbers in the line of sight of quasars offer a tool for the study of the variation of constants (Figure 4.3). Webb et al. 1999 claimed the detection of a significant variation of the fine structure constant α. Accumulating data with years, they confirmed a variation with $\Delta\alpha/\alpha = -0.53(\pm 0.1)\times 10^{-5}$ between z = 0.5 and 3. However, using the exceptional data of the VLT/UVES Large Program "The Evolution of the IGM," we have excluded a variation in the limit $|\Delta\alpha / \alpha| < 0.15\times 10^{-5}$ (Srianand et al. 2007).

The same method can be applied to H2 transitions, which can be detected in some high column density systems, the Damped Lyman-a systems (DLAs). With our 13 recently discovered H2 systems (§5.3), we have obtained the best constraints on the variations of the ratio μ of the proton over the electron mass, with $|\Delta\mu/\mu| < 2\times 10^{-6}$ (Srianand et al. 2010).

Issues remain in these observational constraints on the variations of constants, as all systematic errors are not understood yet. We should be able to increase the number of observed lines by a factor of 3, which would allow measurements for the same lines in different lines of sight, and then reach a much better control of the systematics. A new VLT/UVES Large Program has been recently accepted (34 nights) to obtain data in optimal and controlled conditions. We should reach the limit $|\Delta\alpha/\alpha| < 10^{-6}$ and be able to test new results from Webb et al. on a possible spatial variation of α (Petitjean et al. 2009).

The variation of fundamental constants was the topic of an IAU colloquium organized in 2009 by P. Molaro and E. Vangioni, (IAU Joint discussion 9, Rio, Brazil, Molaro & Vangioni 2010).

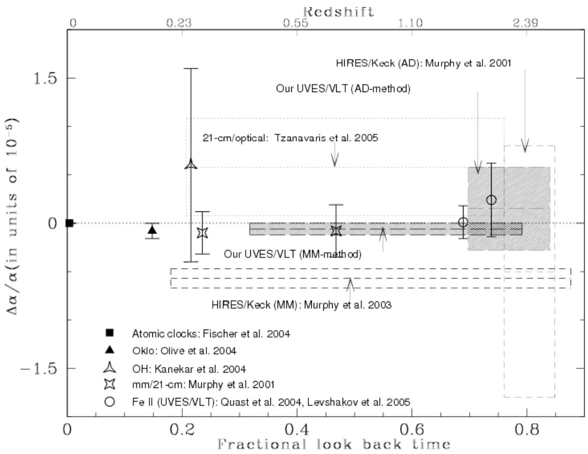


***Figure 4.3** Observational constraints on variations of α.*

4.3 Cosmic Evolution of Baryons

The star formation history is a key parameter to understand the chemical evolution of the Universe, which is driven by the stellar nucleosynthesis. Explosions of massive stars (supernovae or hypernovae, the latter being possibly related to GRBs) play a major role. Starting in 2004, we have developed a model for the cosmic evolution of baryons in the framework of hierarchical structure formation. It is based on a large sample of observational constraints: cosmic star formation rate, reionization of the Universe, chemical abundances at different redshifts and in different sites (structures, IGM), supernovae rates, etc. This model allows in particular characterizing the first generation of stars (population III stars).

4.3.1 Chemical Signatures of First Stars

The Hubble Ultra Deep Field shows that the cosmic star formation rate falls beyond z = 7. A standard stellar formation model (0.1 – 100 $M_{\odot}$) that fits these observations cannot reionize the Universe early enough to reproduce the measurement by WMAP5 of the Thomson optical depth seen by the CMB. Therefore, we have discussed the role of the first stars for this early reionization and also studied their chemical signature. To reproduce the metallicity distribution function obtained by the Hamburg/ESO survey of metal poor stars, an early enrichment by massive population III stars in the range 30 – 40 $M_{\odot}$ seems to be required. Observations in young structures indicate an early He enrichment after the BBN. We have studied the role of intermediate mass population III as progenitors of this element. In addition, we find that the specific nucleosynthesis of Population III stars leads to early chemical abundances in agreement with the composition observed in very old carbon rich/iron poor halo stars (CEMPs). We conclude that these stars have probably been formed at very high redshift from gas enriched by the first generation of stars (Rollinde et al. 2009; Vangioni et al. 2011; see Figure 4.4).

4.3.2 Evolution of Cosmic Rays in the Early Universe and Associated Spallative Nucleosynthesis

^{6}Li observations in Galactic halo stars show a surprising abundance, which is 1000 times larger than the BBN prediction (Hammache et al. 2010). This ^{6}Li abundance seems to be independent from the metallicity, which suggests a pre-Galactic origin. We have built a model for the production of this isotope by spallation in the IGM and we show that an early synthesis of ^{6}Li can be associated to the cosmic rays accelerated in the first structures in the Universe (Rollinde et al. 2008). The same cosmological spallation model predicts a synthesis of Be and B in agreement with observations. However, recent studies show some spectral asymmetries in the observed stars, which suggest that a more detailed analysis is necessary to confirm the high ^{6}Li abundance (Rollinde & Vangioni 2011).

4.3.3 Effects of the Variation of Fundamental Constants on the Evolution of Population III Stars

The variation of fundamental constants affects the rates of the thermonuclear reactions in stars. Due to the high instability of ^{8}Be, the synthesis of ^{12}C by the triple α reaction is highly sensitive to any variation. We have quantified this effect using a nuclear model and studied the evolution of population III stars until He burning (see also chapter 6). At zero metallicity, only the pp chain is available for the nuclear fusion of H, which does not allow massive stars to produce enough energy to stop the gravitational contraction. Therefore, this contraction stops only when the fusion of He starts. H and He fusions become concomitant. The modification of the triple α reaction can accelerate the contraction until the point where only the fusion of H is possible. This leads to a limit of 10^{-5} on $\Delta\alpha/\alpha$ from the consequences on the nucleosynthesis of C and O at z = 15-20 (Ekström et al. 2010).

4.4 Detection and Observation of High Redshift Sources

We participate in several programs for the detection of distant sources and the identification of astrophysical sites where the physical conditions can be measured (star formation rate SFR, chemical composition, etc.) to trace the cosmic history.

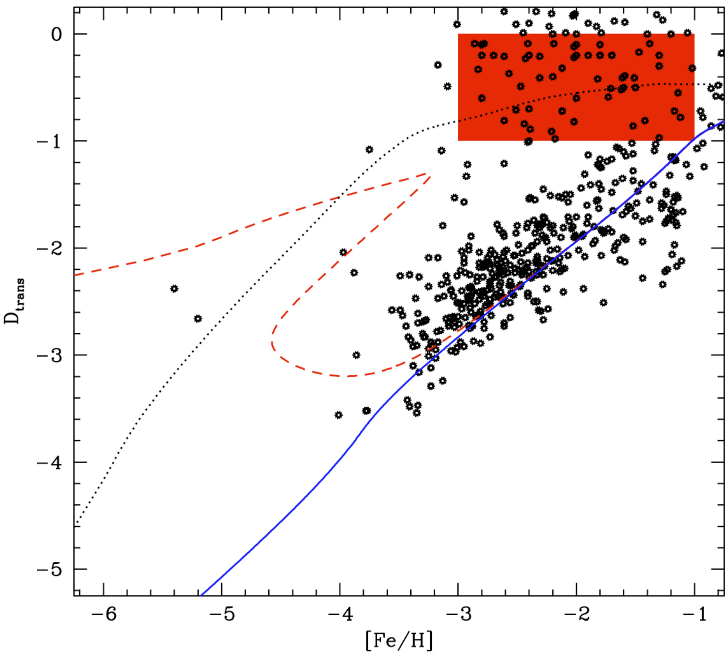


Figure 4.4. *Chemical signature of population III stars. The Dtrans indicator (a function of C, O abundances used as a discriminant of the transition from pop. III to standard star formation, expected for Dtrans >-3.5) is plotted as a function of [Fe/H] for a sample of metal poor stars (ESO data, circles). The blue line corresponds to a chemical evolution model that includes only the normal mode of star formation. The dashed red (resp. dotted black) line corresponds to a model that also includes population III stars in the mass range 35-100 $M_\odot$ (resp. 2-8 $M_\odot$). The red box indicates carbon rich stars that are well reproduced by intermediate mass population III stars.*

4.4.1 Starburst Galaxies

4.4.1.1 Galaxies with the Spitzer Space Telescope – Cosmic Infrared Background (CIB)

Following IRAS and ISO, Spitzer has a strong impact on the study of infrared (IR) galaxies. The Universe at z~1.5-3, corresponding to the peak of the density of ultra-luminous IR galaxies (ULIRGs) and quasars, can now be probed. We focus on the results of the wide area survey Spitzer/SWIRE that reveal new classes of starburst galaxies and AGNs. We collaborate with the Spitzer/SWIRE team to identify massive starburst galaxies at z~2. Several observations have been led at IRAM, with Spitzer spectrograph IRS, and with Herschel in the Far Infrared (FIR) (Younger et al. 2009; Fiolet et al. 2009; Kovács et al. 2010; Fiolet et al. 2010). We show that Spitzer data allow the identification of about 104 ULIRGs in the IR and sub-millimeter range, at z~2, with a very large SFR, a strong PAH emission, and a very large stellar mass. By stacking IRS spectra, we have obtained one of the first detections of H2 at z~2 (Figure 4.5), which implies an unexpected abundance of hot molecular gas (Yan et al. 2010).

We have also mapped at IRAM a deep field at 1.2 mm, with abundant data at other wavelengths, to characterize sub-millimeter sources (Lindner et al. 2011). The pixel flux distribution reaches a very low limit. Our source counting can then reproduce the full intensity of the CIB.

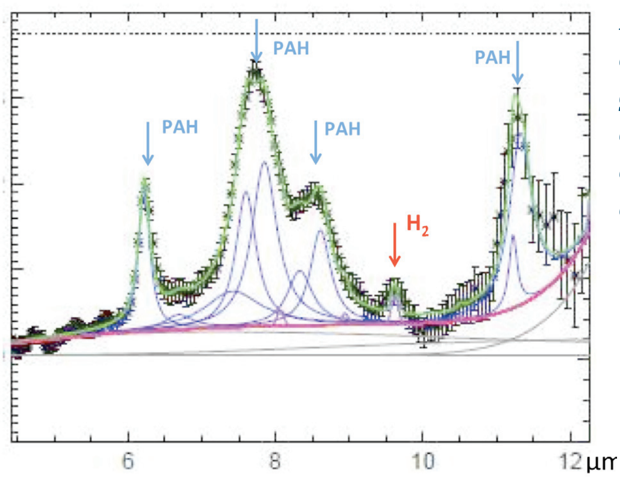


Figure 4.5. *Detection of the H2 molecule at z~2. Stacking of the IR spectrum of 7 galaxies detected by Spitzer at z~2. In addition to four strong PAH spectral bands, a line associated to the H2 molecule is well detected.*

4.4.1.2 Galaxies and Gravitational Lenses in Surveys by the Herschel Space Observatory (sub-mm)

Herschel has a strong impact on the study of galaxies at high z that are ultra-luminous in the FIR: (i) Herschel's spectral range, especially thanks to the SPIRE imager (250-500 µm), covers well the peak of the FIR emission for all redshifts of interest; (ii) the wide surveys led by SPIRE cover a huge area with a good sensitivity (~1000 deg², compared to a total of less than 2 deg² for ground based surveys at λ~1mm). For the first time, the FIR luminosity, and then the SFR, of high redshift starburst galaxies can be measured. About 105 galaxies have been observed in the sub-mm range, which is crucial to trace the large structures.

However, measuring their redshifts remains difficult as Herschel can detect only strong lines. IAP has a significant fraction of SPIRE guaranteed time (see chapter 3). We focus on two topics: the FIR emission from quasars (4.2) and the follow-up at IRAM of strong gravitational lenses in the sub-mm range. The wide area of Herschel's surveys allows detecting rare objects. Identifying sources at z>6 remains difficult and has only started recently. Presently, the most spectacular sub-mm objects are associated with strong gravitational lenses. By extrapolating the first results, one can estimate that Herschel will provide several hundreds of lenses with an amplification factor of 10 or more. To prepare the use of these objects to probe the distant Universe (see chapter 3), we are actively participating in the follow-up at IRAM, which allows measuring the redshift with CO lines, imaging the lensed region with a high resolution, and searching for molecules like H^2O at high z.

4.4.2 Quasars

4.4.2.1 Quasar Search in Large Imaging Surveys

COSMOH leads a program for the search of quasars at all redshifts in large imaging surveys, in order to (i) look for sources adapted for the study of the IGM spatial distribution (e.g. Caucci et al. 2006), (ii) study unbiased DLA samples (e.g. Noterdaeme et al. 2008; Noterdaeme et al. 2009), (iii) study the AGN luminosity function. For this purpose, we have developed photometric selection methods for quasar candidates (Yèche et al. 2010), applied these methods to CFHT Legacy Survey (CFHTLS) and Sloan Digital Sky Survey (SDSS) data. We have made the spectroscopic follow-up of these sources at the Anglo-Australian Telescope (Stalin et al. 2010, 2011). Finally, we are strongly involved in the SDSS-BOSS project (§7.2.6), which will detect about 150 000 quasars at z>2 after five years.

4.4.2.2 High Redshift Quasars: Characterization of the Low-Luminosity Population

With C. Willott (Herzberg Institute of Astrophysics, Victoria, Canada), we have started a program to look for quasars at z ~ 6, with CFHTLS data coupled to near infrared (NIR) observations for a better color selection (Canada-France High-z Quasar Survey, CFHQS). We confirm the redshift of quasar candidates at $5.7 < z < 6.5$ by low-resolution spectroscopy in the red. We obtain a sample of ~25 objects, i.e. twice the previous size at z ~ 6, which includes quasars fainter by 1 to 3 magnitudes compared to the SDSS (Willott et al. 2010). This allows us to determine the quasar luminosity function at z ~ 6 and to estimate the corresponding ionizing flux, which is 20 to 100 times too low to reionize the Universe. This also allows us to predict the number of quasars at larger redshifts that should be detected by present or future NIR surveys. These predictions agree with the recent discovery of the first quasar at z > 7, ULAS J1120+0641 at z = 7.085, in the UKIRT Infrared Deep Sky Survey.

NIR spectroscopy (width of the MgII emission line) of 9 CFHQS quasars at z ~ 6 has been used to measure the mass of the central black hole and to compare with SDSS values. We find a correlation between the black hole mass and the UV luminosity of the quasar; in addition, these quasars have an accretion rate close to the Eddington limit and are therefore in an early phase of exponential growth. The comparison with stellar observations suggests that stars at high z formed much faster than black holes, and/or that only a small fraction of galaxies did have an initial massive black hole.

4.4.2.3 High Redshift Quasars: FIR Emission and Star Formation

We participate in an international program at IRAM for the study of the sub-mm emission from high redshift quasars. Recently, we focused on the quasars at z~6 identified in the SDSS and CFHQS. Almost the whole sample (~50 objects) has been observed at 1.2 mm to estimate the FIR luminosity and the SFR. About 30% of the most luminous quasars in the UV range show a FIR excess, probably due to a starburst. The CO molecule is detected in almost all of them and the ratio CO/FIR is also indicative of a starburst. In addition, CO emission seems to be concentrated in a small radius, possibly a molecular disk or torus. Similar studies have been made for a few obscured AGNs with a dusty environment, detected at z~2-4 by Spitzer. It is now Herschel that can play a major role in the study of the FIR emission from quasars at high z. The first results show that 10 to 15% of quasars are detected in Herschel surveys, which again probably indicates a starburst. This study is still in progress, with a future extension to the large sample of SDSS-BOSS quasars located in Herschel fields.

4.4.2.4 Highly Absorbed Quasars in X-rays in the Chandra Deep Field-South Survey (CDF-S)

The deep surveys made by Chandra and XMM-Newton in X-rays have identified two types of quasars: one, with a low absorption in X-rays, is associated to classical quasars (type-1) and the other with quasars strongly absorbed in X-rays and obscured in optical (type-2). Sources with an extreme value of the absorption in X-rays (Compton thick sources, with log N(H) > 24) still need to be found to reproduce the metagalactic flux in hard X-rays (20-50 keV). This motivates a detailed study in radio, optical (images and spectroscopy) and NIR of weak sources in the CDF-S. A survey at VLA has shown that, despite the identification of a large number of AGNs and starbursts, deep radio surveys are not efficient in discovering this missing population of heavily absorbed X-ray sources. The fraction of sources detected both in radio and X-rays and having a strong absorption in X-rays is smaller compared to a sample selected by X-rays only. A morphology study in optical and NIR leads to the identification of 95% of radio sources in the CDF-S as galaxies at 0.2 < z < 3.7, elliptical or S0 galaxies for the brightest (radio flux > 100 mJy) and star forming galaxies for the faintest (< 100 mJy). The optical spectroscopy at VLT and Keck of the faintest X-ray sources allows measuring the

AGN luminosity function at $L < L^*$ and identifying optically faint starbursts up to $z \sim 2$-3. We also found two structures that trace a thick filament at z=0.67, around a galaxy cluster, with a length of 68 Mpc, and a thinner filament at z=0.73, with a length of 19 Mpc, including AGNs and galaxy groups.

4.4.2.5 Highly Obscured Ultra-Luminous Quasars at z ~ 3.5: Galaxy Mergers or Galactic Outflows?

Two sources at z ~ 3.5, with a strong nucleus activity and a high star formation rate, have been found in the CFHTLS. They are ultra-luminous, with a bolometric luminosity of $10^{13}\ L_\odot$ and a star formation rate of ~1000 $M_\odot$/yr. The AGN is highly obscured (AV ~ 4) and absorbed in X-rays (log N(H) ~ 24.0). The kinematics of the gas (integral field spectroscopy in NIR) and the molecules (CO(4-3) line in the mm range) show that a significant fraction of the ionized and molecular gas reaches velocities larger than the escape velocity. For one quasar, the dynamics clearly shows an outflow due to the AGN, whereas in the second case, the most probable explanations are a wide disk or a galaxy merger.

4.4.3 Gamma-Ray Bursts

COSMOH participates in the SVOM project (Schanne et al. 2009; see also §7.3.5). We estimate the expected GRB detection rate by SVOM, using a Monte Carlo model of the GRB population that was developed for the study of the redshift distribution of these phenomena (Daigne, Rossi & Mochkovitch, 2006, MNRAS, 372, 1034). Our work allows us to predict the number of bursts per class (long, short, X-ray rich, bright or under-luminous, etc.) and to prepare the ground-based follow-up.

4.5 Interstellar and Intergalactic Medium Spectroscopy

4.5.1 Spectroscopy Along the Line of Sight of Quasars

4.5.1.1 Large Spectroscopic Surveys of Bright Quasars

The observation of HI and ionized metals absorption lines in the spectrum of distant quasars is a unique tool to study the IGM and the ISM of galaxies at large redshift. Many programs are in progress, with observing time at VLT, especially with UVES and FORS but also X-SHOOTER and Sinfoni. In particular, a collaboration with many astronomers from ESO member countries leads a VLT-UVES spectroscopic survey of absorption lines in bright quasar spectra (VLT-UVES Large Program, PI: P. Molaro; Co-I P. Petitjean, 34 nights), and another specific large survey for molecular hydrogen has obtained more than 50 nights at VLT (PIs: P. Petitjean, C. Ledoux, P. Noterdaeme).

4.5.1.2 Origin of the Excess of Absorbers in the Line of Sight of Blazars

The surprising excess of MgII absorbers found in GRB afterglow spectra compared to quasars motivates a study to measure the mean number of absorbers in blazar spectra, since blazars show some similarities with GRBs. A program of 8 nights with VLT-FORS1 has allowed us to observe 42 blazars and to show that the excess of absorbers (factor 2) in blazars is similar to GRBs. We have explored a scenario where high velocity gas is dragged by the AGN jet that points towards us (Bergeron, Boissé, Ménard 2011). To test it, we have observations in progress at VLT-UVES looking for temporal variability or partial coverage of the source continuum in the absorption lines of some blazars.

4.5.2.3 Detailed Study of a Neutral Absorber Associated with a Group of Galaxies

A remarkable absorption system at z=0.66 in the spectrum of the quasar PKS2126-158 (VLT-UVES large program led by J. Bergeron) has been selected for a detailed analysis of the properties of the neutral ISM in distant galaxies. This system shows strong CaI and NaI lines in a velocity range that reaches 500 km/s. Constraints from observations at 21 cm at WSRT and from deep images of the same field indicate that the absorption is probably due to gas expelled by tidal forces within the group of galaxies located in front of the quasar at z = 0.66 (Boissé, Gupta, Srianand, in preparation).

4.5.2.4 Metal Enrichment of the IGM and/or the Circumgalactic Medium

The issue of the missing baryons (~ 40%) at z~0 and the missing metals (~50%) at z~2.5 can be solved by the existence of a warm IGM (T ~ 10^5 to 10^6 K). Such a medium is identified thanks to OVI absorption lines associated with the Ly-α forest in the spectrum of distant quasars. The metal enrichment of the IGM or the circumgalactic medium appears very inhomogeneous. A preliminary study shows that the distribution of the O abundance at z ~ 2.3 is bimodal with two peaks at 50% and 1% of the solar value. The metal rich population contributes to 50% of the cosmic density of oxygen. The heating mechanism of this phase is not well established. A recent study of a large sample at z ~ 2.3 shows that only a small fraction of these OVI absorbers trace a unique, photo-ionized phase in equilibrium. Most of these systems have a temperature $T<10^5$ K, which excludes the possibility of gas in collisional equilibrium, and must be multi-phase. The non-thermal velocities that are observed suggest that these systems trace either galactic outflows, or a medium initially heated by shocks and currently cooling radiatively. The measure of the metallicity is in progress for the systems with a low HI column density, where a unique phase with a high degree of ionization can be assumed.

4.5.2 Spatial Structure of the IGM

We observe pairs of quasars with an angular separation of 1 to 3 arcmin and we study the correlation between the absorption lines found in each line of sight to probe the spatial distribution of the IGM. This allows us to find structures on distance scales comparable or greater than the separation. This study is a substantial part of the PhD project of Hayley Finley. Such pairs of quasars can also be used to make the first Alcock-Paczinsky test to measure the geometry of the Universe by comparing the transverse and radial correlations. These measures will soon constrain in an independent and original way the density of dark energy Ω_Λ (e.g. Rollinde et al. 2003). In the future, it should be possible to observe groups of quasars in the same field and to inverse the absorption lines found in the lines of sight to reconstruct the 3D density field. We have developed inversion methods and we study statistical methods to obtain the topology of the IGM (Caucci et al. 2008). The simulations that we use must be normalized with the observed mean absorption in the IGM, and its evolution with z. This requires normalizing quasar spectra, which implies systematical errors that have been evaluated during the thesis of Ali Aghaee and Isabelle Pâris (Aghaee et al. 2005; Pâris et al. 2010).

In its vicinity, the quasar ionizing flux decreases the Lyman absorption in the observed spectrum, compared to the mean absorption (proximity effect). A matter over-density around the quasar can compensate for this effect. These two effects in competition have been analyzed in quasar spectra from the VLT-UVES Large Program at z=2 and 3 (Rollinde et al. 2005), and then at z>4 at Keck (Guimaraes et al. 2007). The localization of quasars in dense environments is confirmed. The transverse proximity effect can now be tested with BOSS data (Rollinde et al. in preparation).

4.5.3 Search for Molecules at High Redshift

4.5.3.1 Search for Molecules in Damped Lyman-α Systems (DLAs)

DLAs at high redshift show a high density column and are therefore considered as the precursors of galactic disks. As the gas is neutral, metal abundances can be precisely measured and these systems are used for the study of the chemical evolution of the Universe. Our group has led the first systematic search of H2 in these systems, by observing ~70 quasars with VLT/UVES (Noterdaeme et al. 2008). We have detected H2 in 15 systems and CO in 5 systems, resulting in more than 15 published papers. The detection of molecules seems to be strongly correlated with the gas metallicity: H2 is detected in 40 % of systems with metallicity greater than 1/20 of the solar value (Petitjean et al. 2006); the gas properties can be studied in detail (Noterdaeme et al. 2007, 2010). Gas in DLAs is surprisingly homogeneous, except in the molecular components where metal depletion on dust can be important (Srianand et al. 2008). Thanks to these studies, CO and HD are now detected in a systematic way in the ISM of distant galaxies. Finally, a large survey of the 21cm absorption in DLAs with intermediate redshifts at GMRT (>300h, Gupta et al. 2009; Srianand et al. 2010) and at high redshift with

GBT is in progress. We are also associated with the MALS project for a systematic survey of the absorption at 21 cm at z<1.8, which has obtained 4000 h to observe with MEERKAT, a precursor to SKA.

4.5.3.3 Temperature of the Cosmic Microwave Background Radiation (CMB) at High Redshift

The standard Big Bang theory predicts that the CMB temperature increases linearly with redshift, due to the adiabatic expansion of the Universe. This has to be tested with direct measurements. Due to its large dipolar momentum, CO can be in radiative equilibrium with the CMB. This molecule, when detected in the ISM at large redshift (see 4.5.3.1), can therefore be used as a thermometer to measure the cosmic evolution of the CMB temperature. Our results at $1.7 < z < 2.7$ show that the measured temperatures are in perfect agreement with the standard theory (Noterdaeme et al. 2011): see Figure 4.6.

4.5.3.2 Search for H2O in Gravitationally Lensed Herschel Galaxies

Among the possible uses of the exceptional gravitational lenses found by Herschel (4.1), our group is an expert in the search at IRAM for H^2O at large redshift. After one of the first detections (Omont et al. 2011), two other detections have been confirmed in 2011, one at z~6. The rotational levels of H^2O having large energies, the large luminosities of these systems imply peculiar conditions for the excitation and the chemistry in the nucleus of these galaxies, possibly due to a powerful AGN. The systematic study of H^2O lines in Herschel lenses will continue, especially thanks to ALMA, in order to use this diagnostic to characterize these peculiar conditions in a large sample of distant sources.

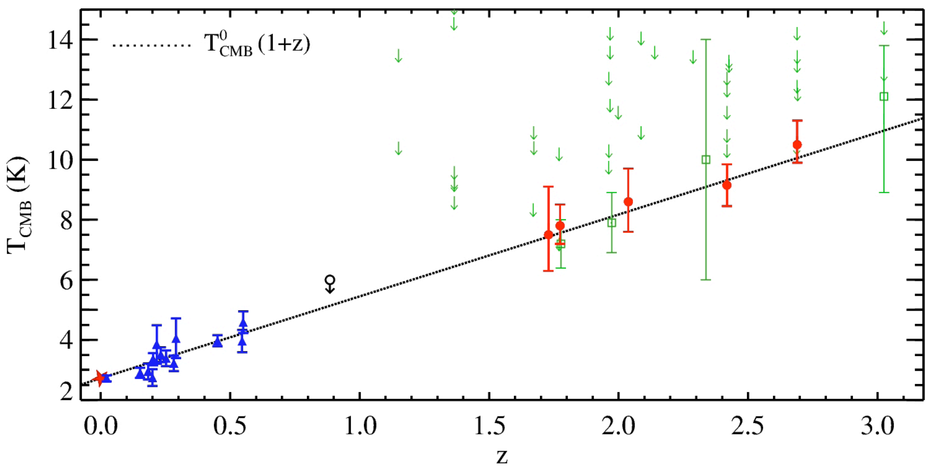


__Figure 4.6.__ CMB temperature as a function of redshift. The red star indicates the measured value at z=0. Our measurements based on the rotational excitation of CO are plotted as red dots at $1.7 < z < 2.7$. Other measurements at z >0 are based on (i) the Sunyaev-Zeldovitch effect ($z < 0.6$, Luzzi et al. 2009) and (ii) the analysis of carbon fine structure lines (Cui et al. 2005, Ge et al. 1997, Srianand et al. 2000, Molaro et al. 2002). Upper limits are provided by the analysis of neutral carbon (literature + our UVES sample, Srianand et al. 2008) and molecular absorption (z=0.9, Wiklind & Combes 1996). The straight line indicates the prediction of the standard Big Bang theory.

4.5.4 ISM: Observation and Modeling

To understand the origin of the highly excited H_2 gas detected by FUSE in the line of sight of the runaway star HD34078 (Boissé et al. 2005), we have mapped the CO emission with the 30 m telescope at IRAM. It is clearly associated with HD34078 and shows a remarkable bow shock structure, due to the interaction between the stellar wind and the dense interstellar cloud. We have monitored the variations of the CH and CH^+ absorption lines to study the small-scale structure in the gas. Thanks to a reference star (ζPer), we were able to confirm the variations observed before 2005. The variability is associated to the shocked region. On the other hand, the H_2 gas that is not affected by HD34078 does not vary and therefore does not show any important small-scale structure (Boissé et al. 2009). Several complementary studies are in progress. A detailed mapping of the CO emission around HD34078 is done at IRAM in collaboration with J. Pety to better determine the geometry of the shocked region. Such a remarkable and well-characterized interface between ionized and neutral gas can be used in the future as a reference case for models. The photometric follow-up of HD34078 (AE Aur, labeled as variable) is currently done with F. Teyssier to understand the possible link between the variations observed by Hipparcos and the stellar wind/interstellar cloud interaction. Finally, the excellent quality of our data on ζPer will allow us to study the small-scale structure in the "standard" un-perturbed cloud located on the line of sight (project in collaboration with S. Federman).

4.6 Outlook

There are many indicators of the dynamic nature of the research group COSMOH: the arrival of two new permanent researchers in 2010 and 2011, the number of PhD students, our many successful national and international collaborations, the selection and funding of several of our projects by the ANR. Our research program is at the interface between cosmology and high-energy astrophysics. Our expertise in the studies summarized above is recognized internationally, and we will continue our research in these areas: the physics of accretion onto black holes, notably the formation and evolution of supermassive black holes, an area which is strengthened by the recent arrival of M. Volonteri; the physics of gamma-ray bursts, for which we have developed a unique and complete set of self-consistent modeling tools that can be adapted to other relativistic jets in the future; the Big Bang Nucleosynthesis with an original program to test new physics (ANR project VACOUL; ESO Large Program); the search for high redshift sources and the characterization of these objects, with a great involvement in large imaging surveys and the multi-wavelength follow-up of the sources; the spectroscopic probing of many different astrophysical sites (collapsed structures and their interstellar and circumgalactic medium; forming structures; intergalactic medium) at all redshifts, particularly with world-recognized expertise in the observational constraints on the variations of fundamental constants, in the search for molecules at high redshift, an area recently strengthened by the arrival of P. Noterdaeme, and in the determination of the spatial distribution in the intergalactic medium; the modeling of the cosmic evolution of baryons from the first stars to the present Universe, which is based on many constraints, in particular those provided by observations done within COSMOH, and which is complementary to other more frequently used approaches (see also the BOSS project in chapter 7).

There is a favorable instrumental environment for our projects: at high energy, the Fermi satellite was launched in 2008 and should continue to observe for many years to come. In light of a future extension of our theoretical work on gamma-ray bursts to other relativistic jets, very high-energy gamma-rays may be accessed observationally by ground-based Čerenkov telescopes, such as HESS and – in the future – CTA. In the hard X-ray/soft gamma-ray domain, the near real-time localization of gamma-ray bursts should suffer a slowdown after the end of the Swift mission in a near future, but should hopefully start again with SVOM around 2017. In between, the low-energy instrument GBM on board Fermi will still detect gamma-ray bursts. Many instruments will be available for the multi-wavelength follow-up of gamma-ray bursts detected by SVOM. Even a new non-photonic window may open using gravitational waves, as Advanced VIRGO/LIGO should reach the sensitivity for the first detections of neutron star mergers, which are probably the precursors to short gamma-ray bursts. More generally, our multi-wavelength exploration of the distant Universe will benefit of many existing or coming instruments, such as HST, IRAM, Spitzer, Herschel, APEX, Planck, CFHTLS, WIRCAM, VISTA, Meerkat, SKA, ELTs…

Our group will take advantage of these instruments to multiply precise measurements in different astrophysical contexts, with an increase of the covered redshift interval, and possibly the ability to probe directly the end of the dark ages and the epoch of formation of the first stars. We will focus on providing fundamental constraints for models of the cosmic evolution, and original tests for new physics. In parallel, we will continue with our theoretical work on the processes governing the cosmic evolution of baryons, and on the modeling of high-energy sources. Within IAP, the studies led by COSMOH show many connections with other research groups, especially the GreCO (variations of constants, acceleration mechanisms, electromagnetic counterparts of sources of gravitational waves), the group “Large structures and deep Universe” (measurements of cosmological parameters, large scale structure of the Universe, formation and evolution of structures and supermassive black holes), the group “Galaxy formation and evolution” (characterization of supermassive objects at high redshift, history of the activity in galactic nuclei) and the group “Extrasolar planets and interstellar medium” (study of the local interstellar medium).

To summarize, the research program of the group “Cosmology and High-Energy Astrophysics” for the coming years relies on the expertise we have built in this field for obtaining observations of the best quality and for their physical interpretation, and keeps always in mind the purpose of developing a global self-consistent picture in a cosmological framework.

Large Scale Structures and Deep Universe

5

The research group "Large Scale Structure and Deep Universe" consists of:

13 researchers/research enginneers CNRS: François Bouchet, Stéphane Colombi, Jacques Colin, Bernard Fort, Raphaël Gavazzi, Eric Hivon, Roya Mohayaee, Christophe Pichon, Simon Prunet, Alain Riazuelo, Sebastien Peirani, Thierry Sousbie, Jean-François Sygnet.

5 astronomers: Christophe Alard, Karim Benabed, Emmanuel Bertin, Henry J. McCracken, Yannick Mellier.

1 Professor at UPMC: Benjamin Wandelt

In the time frame 2007-2011:

12 post-doctoral researchers: Soumen Basak, Aurélien Benoit Levy, Richard Bielby, Pawel Bielewicz, Yohan Dubois, Franz Elsner, Silvia Galli, Catherine Heymans, Martin Kilbinger, Anna Mangilli, Sébastien Peirani, Thierry Sousbie.

18 PhD students: Christopher Bonnett, Florence Brault, Sandrine Codis, Jean Coupon, Typhaine Dechelette, Anne Ducout, Ophelia Fabre, Liping Fu, Christophe Gay, Guilhem Lavaux, Michal Maciejewski, Alice Pisani, Guillaume Plum, Raphaël Sadoun, Jérome Thiébaut, Hong Tu, Flavien Vansyngel, Melody Wolk.

8 PhD thesis were defended: Christopher Bonnett, Jean Coupon, Liping Fu, Christophe Gay, Guilhem Lavaux, Michal Maciejewski, Jérome Thiébaut, Hong Tu.

HDR: 9

Publications: I: 381, II: 68

The research group "large scale structure and deep Universe" devotes its activities to the studies of large-scale distribution of matter in the Universe. Large-scale structures provide direct information on the properties of the Universe and can be compared to the theoretical predictions of cosmological models. Activities of the research group encompass theoretical modeling of cosmological model, survey observations and statistical analysis, and numerical simulations bridging the two first components. More specifically, the theoretical works focus on phenomenological studies of different primordial cosmological models to derive properties that can be observed and then, to confront them to observational constraints. These tasks have required the development of many new mathematical and statistical tools needed to compare theoretical predictions and observational constraints. These developments represent a large fraction of the research group activity, which can be used internally by people working on numerical simulations and large observational surveys. Most of these tools are made available to the community as common tools.

Most of the recent cosmological models are too complex to be only analytical. They must be studied through heavy numerical simulations that are used to calculate the properties of the model, and their variations, as a function of the values of the model parameters, require most of the time in statistical approach. The numerical simulations are also used to generate large data sets in a form that can be directly compared to observational surveys. The research group is involved in running large numerical simulations, but have also strong expertise in the development of visualization and statistical analysis tools to facilitate this comparison.

On the observation side, the research group develops four approaches: direct detection of dark matter, characterization of dark energy, use of gravitational lensing in strong and weak modes, and studies of the cosmological microwave background. These two last topics are supported by direct link to observational projects like the Canada-France-Hawaii Telescope legacy survey (CFHT-LS) and the space mission EUCLID in the coming years for weak lensing, and Planck Surveyor for the CMB, and are associated with large data centers hosted and operated by IAP: TERAPIX for the wide field imaging and Planck Data Processing Center (DPC) for Planck.

Data analysis from the Planck mission feeds theoretical cosmological studies at IAP, and takes advantage of the skills developed in the research group. The presence of the Planck DPC is an asset for the research group, which benefits from the direct expertise of the people working on the data. This combination of theory, numerical simulation and data processing is unique in France. It places the research group at the forefront of the CMB studies in the future. Combined works on the CMB and the lensing will be also part of the activities of the group.

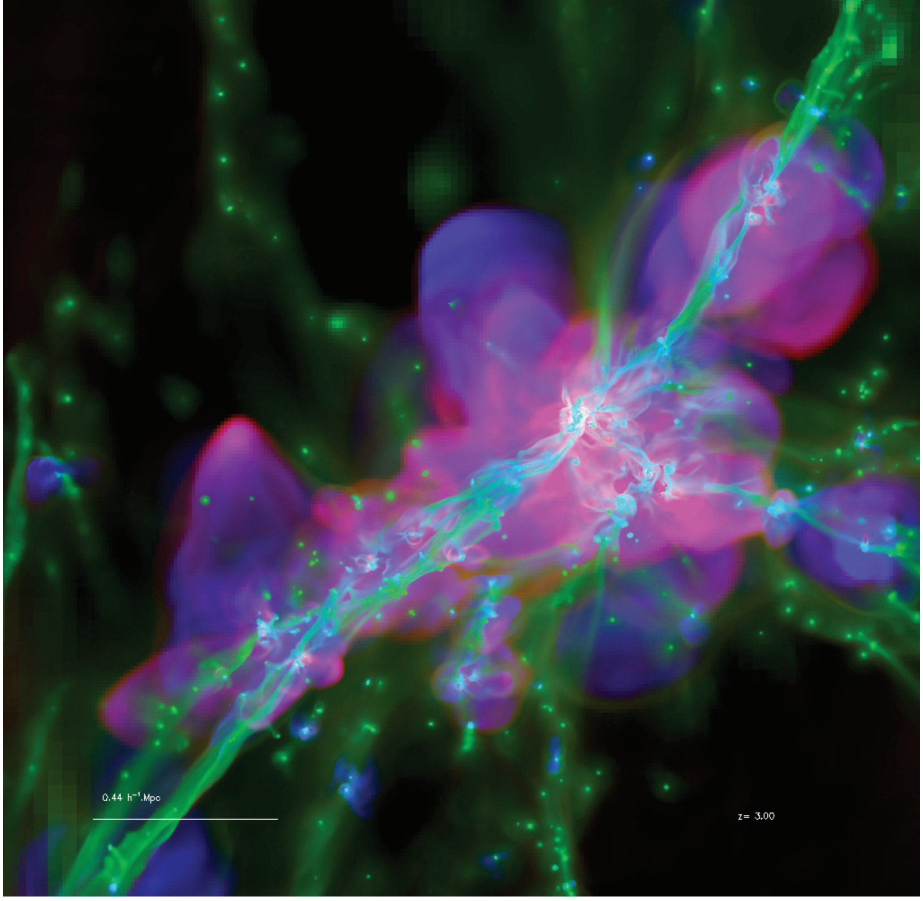


Figure 5.1. Cosmic environment of the galaxy NUT at redshift 3. The density is in green, metals in red and temperature in blue. Angular momentum advection along the filaments can explain the hierarchical formation of the central disk.

Following the success of the Horizon project, with a strong involvement of the IAP, numerical simulation are, and will remain, one of the top IAP priorities. The recent hiring of two talents S. Peirani and T. Sousbie, together with the contribution to the international Horizon-UK (Figure 5.1, Kimm et al. 2011) will foster this domain. From past experience, the availability of synthetic data is key to develop innovative method for large data processing. And it is mandatory to continue to strengthen these activities within the IAP, to follow up the next generation of cosmological observations in which the IAP is engaged like surveys in the near IR with VISTA in ESO, or later the ESA mission EUCLID. The leading role of IAP in wide field astronomy should be maintained in the future with a combination of strong involvement in observation programs, and developments of numerical simulations and associated tools.

5.1 Cosmological Microwave Background

5.1.1 Planck Mission

This chapter complements the project technical description in Chapter 7.2.1. After a first step devoted to understand and to analyze the pointing of the satellite and the perturbation generated by the motion of the satellite (orbital-dipole), the first scientific analysis has started 3 months after the launch in May 2009 (Lamarre et al. 2010, Tauber et al. 2010). The first non-cosmological results have been published in Astronomy and Astrophysics (Planck Collaboration 2011, 24 references). The test of cosmological models against the Planck observation of the CMB is ongoing since 2011.

The research group led by François Bouchet is heavily involved in the Plank-HFI operation and data analysis. Among other things, the IAP's research group in collaboration with ESA engineers had the responsibility to produce and to distribute to the consortium the satellite pointing timeline. New algorithms were developed for every step of the data processing: from instrumental noise characterization to probability exploration of cosmological parameters. This last part uses development made in the framework of the interdisciplinary ANR grant, ECOSSTAT. Accurate calibration of the instrumental response from data obtained in flight, and a likelihood model to tight the observational results and the cosmological models have been derived. The effects of the standard method to separate the CMB emission from other astrophysical components, the so-called Internal Linear Combination (ILC), on the power spectrum of temperature (Saha et al. 2008) and polarization (Samal et al. 2010) anisotropies were analyzed. Due to its non-linear properties, despite its name, this method generates biases for the estimation of the power spectrum in filtered maps. With some assumptions on the contaminants, analytical solution can be found for these biases. A power deficit was found in the quadrupole component of the temperature anisotropy, due to this bias.

Optimal maps of the CMB have been produced taking into account the 1/f noise, which generates a long-term time component of the noise, as well as the statistical noise residuals. Pre-flight measurements were used to analyze their impact on scientific products. In particular, the complex shape of the beam patterns was analyzed in depth. As first step toward good uses of the Planck data, as well as any CMB experiment, a new method to determine the likelihood of the angular power spectrum of the CMB at large scale was implemented. Some thought has been given to look in the new opportunities opened by the polarization of the CMB to understand the primordial Universe and to detect gravitational waves, relic of the inflation era.

One of the research group member (Eric Hivon) is maintaining the software library HELPIX, which is available on http://sourceforge.net/projects/healpix/. This package offers the capability to pixelize the sphere. It has been used for WMAP and Planck, but also in many other areas, like exoplanets or High-energy cosmic rays. Polarization and non-Gaussianity has been looked at in the Boomerang data, in addition of the measurement of Sunyaev-Zeldovich effect (Veneziani e t al. 2009). Data obtained with the BICEP instrument in South Pole to measure the CMB polarization on large scale have been analyzed.

5.1.2 CMB and Large Scale Structures

5.1.2.1 CMB and the Models of Structure Formation

Studies of rare events in a distribution, like the hottest or coldest areas in the CMB, or he largest clusters of galaxies existing in the Universe, offer interesting constraints on the models of formation of Large Scale Structure. In collaboration with University of Oxford, an analytical theory has been used to predict the distribution of maxima expected in an area of a given size for a Gaussian random field (Colombi et al. 2011, see also Gay, Pichon et Pogosyan 2011, Figure 5.2, bottom). Another analytical calculation was made to predict the mass of the largest cluster of galaxies in a given volume of the Universe (Davis et al. 2011). Both calculations have been validated by numerical simulation, the 4Π simulation among others.

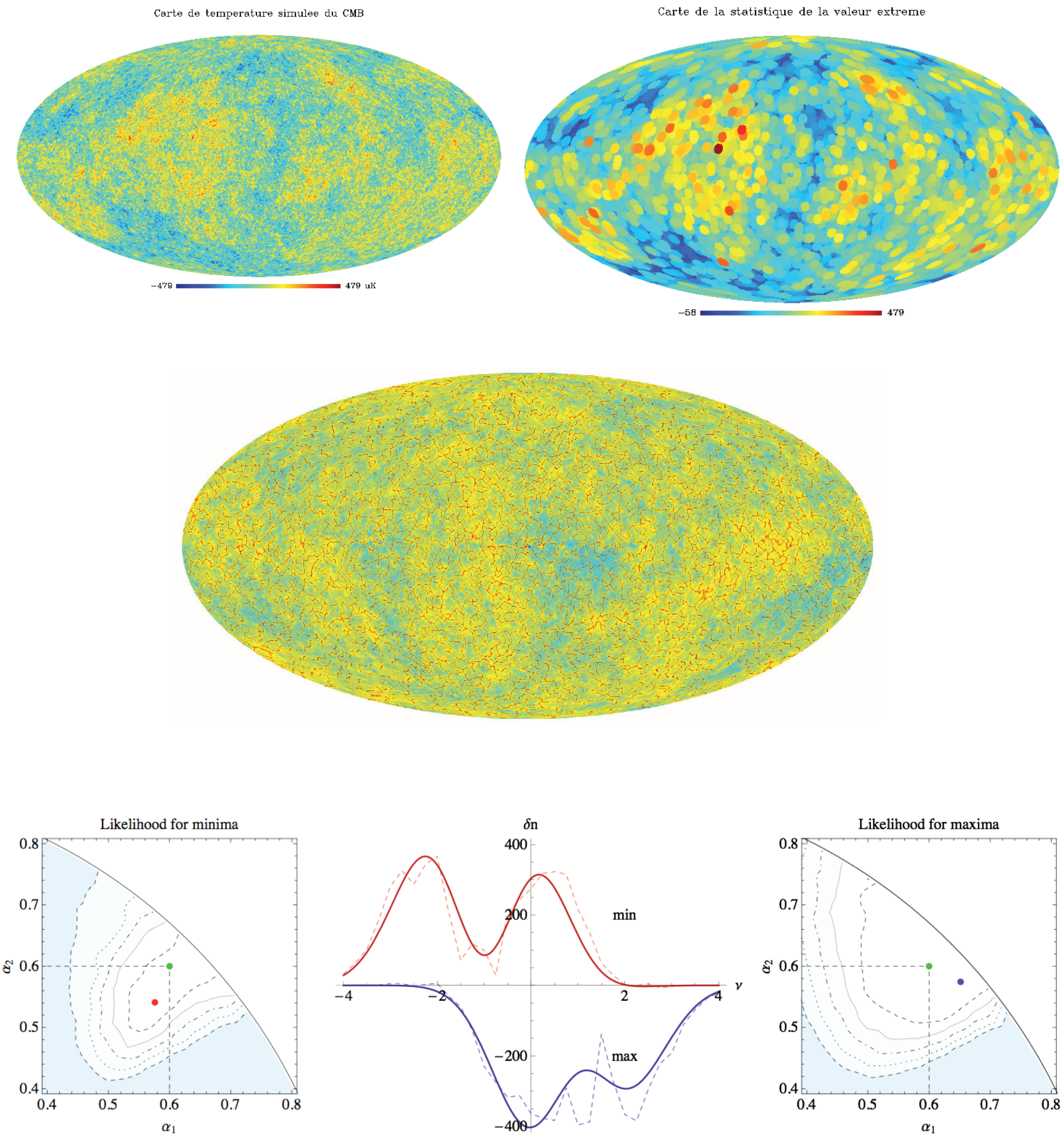


Figure 5.2. *Top, on left a randomly Gaussian field simulated on a sphere. On right the map of the statistic of measured maxima in disk centered on each pixel. It is easy to guess what was the size of the disk used. In first approximation, this map can be derived from the distribution of local maxima. Center: persistent skeleton of the WMAP map. Bottom, center non-Gaussian correction to the extrema counts on the CMB map, with likelihood isocontours on left and right.*

5.1.2.2 CMB and Gravitational Lenses

K. Benabed is leading an international working group (about 20 people, including 2 post-docs at IAP) to study the effect of gravitational lenses in the CMB observations. This effect has been characterized by Basak et al (2009). This has been used to develop a numerical code of weak lensing by large-scale structure of the CMB. The Planck consortium now uses this code.

A likelihood estimator for the statistical properties of the Planck results has been built. Such mathematical tools are needed to extract values of the cosmological model parameters from the Planck data, and to improve the quality of the models. This project has taken place in the framework of the ANR grant ECOSSTAT (2005-2009, IAP, LAM in Marseille and laboratories from TSI of Telecom-Paristech et CEREMADE, University Paris Dauphine). The goal of this approach was to improve the tool to analyze the statistical properties of the data, and to merge them in a coherent mathematical representation. The results have been published in four main papers (see Figure 5.3). The first one presents the method to merge data from different origins (Kilbinger et al, 2009) that had allowed to combine for the first time the results from the supernova distance scale and the weak lensing measured in the CFHT-Legacy Survey together with the CMB measurements. With the same data sets Wraith et al have developed a new Bayesian analysis tool, discussed in a second paper. A particular features of this method makes possible the comparison between different cosmological models with simple criterions has been described in a third paper (Kilbinger et al, 2010). A specific application to the statistical characterization of the anisotropy of the CMB temperature fluctuation at large scale has been published in a fourth paper (Benabed et al, 2009). This work is the first application in astrophysics of likelihood determination based on copula approximation. This now widely used in the Planck consortia, and by other research groups. The code is publicly available on www.cosmopmc.info.

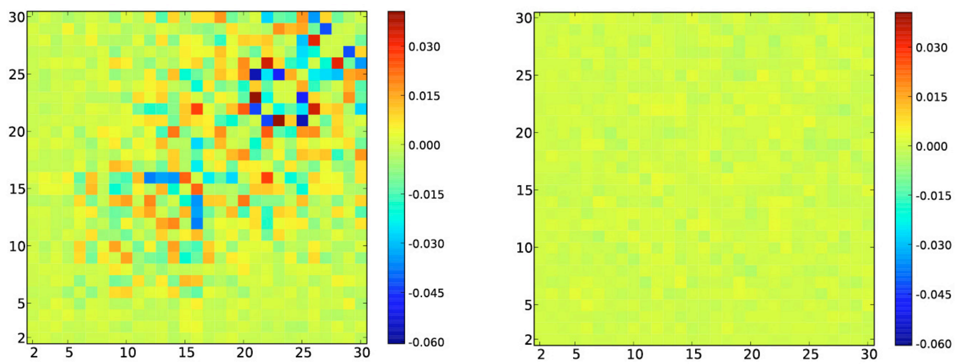


Figure 5.3. *Measure of the low multipole correlation for the anisotropy of CMB temperature. On the left, the correlation calculated from the WMAP data with a Monte-Carlo integration, which took 700 hours of CPU, on the right, the difference between this result and the result obtained using the Benabed et al method. Differences are very small, and within the accuracy of the Monte-Carlo method.*

The CFHT-Legacy Survey (CFHT-LS) has been used to determine the excess of coherent alignment of the ellipticity of background galaxies at large and intermediate scale. Numerical code has been developed to link cosmological models and observations. These codes are now part of the ECOSTSTAT toolbox. Implication of the CFHT-LS observation and constraints on cosmological parameters are described in Fu et al (2008). A new analysis of the lens effect on the COSMOS survey has been performed using these tools, leading to the first detection of the acceleration of the Universe expansion based on lensing effect alone. (Figure 5.4 and Schrabback et al, 2010)

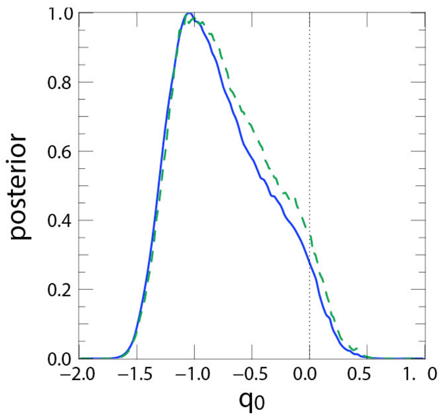


***Figure* 5 4.** *Density probability for a Universe in accelerating expansion (q0 <0) from the COSMOS observation. In the blue curve, the probability for an accelerating Universe is 95%.*

5.1.3 CMB and Primordial Cosmology

Several new approaches have been initiated to constrain the initial condition in the Universe, and more specifically its properties in the very high-energy era, close to the Planck scale, well above what can be achieved with a particle accelerator on Earth. Smith, Kamionkowski and Wandelt (2011) have shown that the non-Gaussianity measurements generate new constraints on the process creating the primordial perturbations. Planck will be the next step in the determination of primordial non-Gaussianity, improving by a large amount the WMAP results. Ben Wandelt is co-lead of the non-Gaussianity group in the Planck consortium. He, and his group, are developing new tools to measure the non-Gaussianity from the Planck data, as well as modeling the effect of the instrument on these measures The analysis of the statistics of the skeleton length of the CMB anisotropy is another promising tool to analyze the non-Gaussianity (Zhan et al, 2010).

Using the parallel processing of graphics processing units, Elsner and Wandelt (2011) have developed a new approach to compute N points correlation on a sphere, improving on CPU time to compute the inference of cosmological parameters on CMB at the angular resolution of Planck. Lavaux and Wandelt (2010) have developed a new fast method to simulate gravitational lensing for the CMB linked with the mass distribution on the way from the last diffusion surface. This method is based on the statistics of voids, (see Figure 5.5)

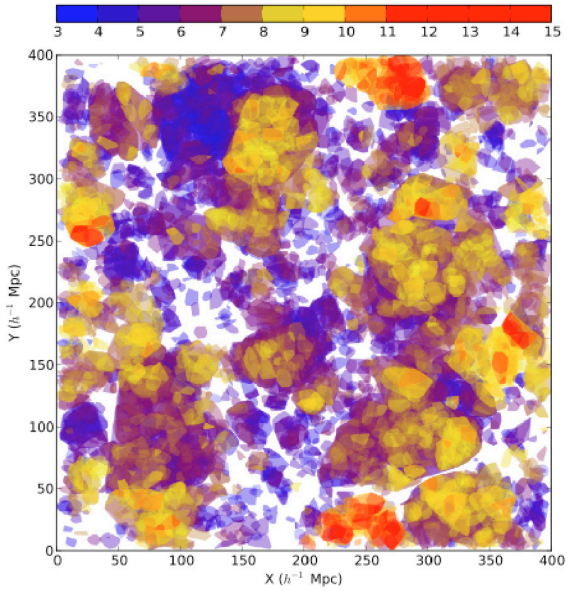


Figure 5.5. *Hierarchical tree of voids leading to new constraints on the dark energy.*

Bayesian techniques initially developed for CMB analysis have been applied to the statistic of large structure surveys. Jasche and Wandelt (2011) have shown that these techniques can provide a better definition and even decrease the errors in photometric redshift. Absorption of CMB emission by the 21 cm hydrogen line could constraint mechanism beyond the standard model like a variation of fundamental constants or the existence of cosmic string network. Numerical simulations of the signature of these effects have been performed (Sutter, Wandelt and Malu, 2011) with implication for the design of next generation instruments. These approaches will continue to be developed with the CMB observations of Planck, the dark energy survey with the LSST and later EUCLID, combined with theoretical studies. This will part of the goals of the ICAP project (Initiative en Cosmologie et en Physique des Particules) created by the merging the ERC DARK MATTERS project of Pr. J. Silk and the B. Wandelt "Chaire d'Excellence".

Cosmic shear can also be used to track signature of quintessence model. The first study along these lines has been done using the VIRMOS-Descart and the CFHT-LS surveys (Schind et al, 2007). In a first approach, plausible models (Ratra-Peebles or supergravity potential) have been used and their impact on the cosmic shear computed. These models produce a slow start of the acceleration of the expansion of the Universe, and are barely compatible with the observation. A more phenomenological approach was developed to determine what are the characteristics of the quintessence fields that are compatible with the observations of supernovae. First encouraging results were obtained (Douspis et al. 2008, Ferramacho et al. 2010).

5.2 Probing Large-Scale Structure with the Weak Lensing of Background Galaxies

Weak gravitational lensing due to the cumulative effect of large structure encountered by photons emitted by distant galaxies modify the apparent shape of galaxies. On large scale, it produces the so call Cosmic Shear. Statistical studies of the Cosmic Shear provides direct information on the growth of structure in the Universe, and therefore on the dark matter distribution at all scales, and on the source of the acceleration of the expansion. But this requires a very accurate measurement of the galaxy shape, as well as a rough distance determination, by photometric redshif for example.

IAP is one of the world leaders for Cosmic Shear studies. In the recent years, the focus has been put on the CFHT-LS and the HST COSMOS surveys, and the preparation of the ESA EUCLID mission.

In 2008, the products of the CFHT-LS Wide became available. Photometric results have been measured by Coupon et al (2009), while the cosmological implications are described in Fu et al (2008). This work remains today the best analysis based on a large survey of the Cosmic Shear. Combining these results of the CFHT-LS, with results of other probes, supernovae from the SNLS and CMB from WMAP, and using a Markov Chain – Monte-Carlo techniques, Kilbinger et al (2009) have shown that all these constraints, put together, are compatible with a cosmological constant. Following these first studies, a larger consortium, from Europe and Canada have been created, the CFHTLens, with a goal to reduce by a factor 2 to 3 systematic effects on the CFHT-LS (see Figure 5.6). Several improvements have been obtained in the PSF determination, the measurements of the shape of galaxies and the accuracy of photometric redshifts. In addition, the effect of intrinsic alignment of galaxies has been taken into account. This has required 3 years of effort, in particular from C. Bonnet and Y. Mellier at IAP, leading to some twenty papers submitted end of 2011. The first one has been published early 2012 (Hildebrandt et al. 2012).

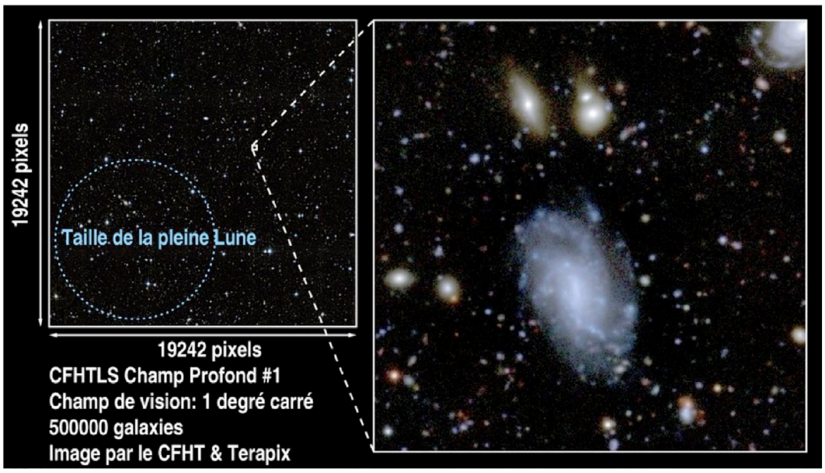


Figure 5.6. *a deep field of the CFHT-LS.*

The HST COSMOS survey is complementary of the CFHT-LS with a better image quality and detection limit, but on a much smaller field. A weak lensing tomographic analysis of the COSMOS field, using Ilbert et al (2009) photometric redshifts has produced the first independent determination of the accelerated expansion of the Universe (Schrabback et al., 2010). This work is a precursor of what will be achieved by the EUCLID space mission. IAP is heavily involved in the preparation of this mission (see Chapter 7.2.3). Y. Mellier is the Chair of the Euclid Consortium Board, and K. Benabed is leading one of the working groups on weak lensing.

Pichon et al (2010) have addressed the issue of reconstructing convergence maps (from ellipticity measurements on a significant fraction of the celestial sphere). They made use of kappa maps derived from the Horizon-4π simulation and applied regularized inversion methods developed elsewhere. This investigation suggest that the inversion deals well with masks and contamination associated with B-modes; it can also tackle a non-linear model, and quasi point like clusters on the map while relying on an auto-calibrated penalty. They also implemented the skeleton (see below) as a diagnosis to quantify the quality of the reconstruction. Finally they demonstrated that penalization is very effective at extrapolating convergence within the masks (see Figure 5.7, Teyssier et al. 2010, Pichon et al 2010).

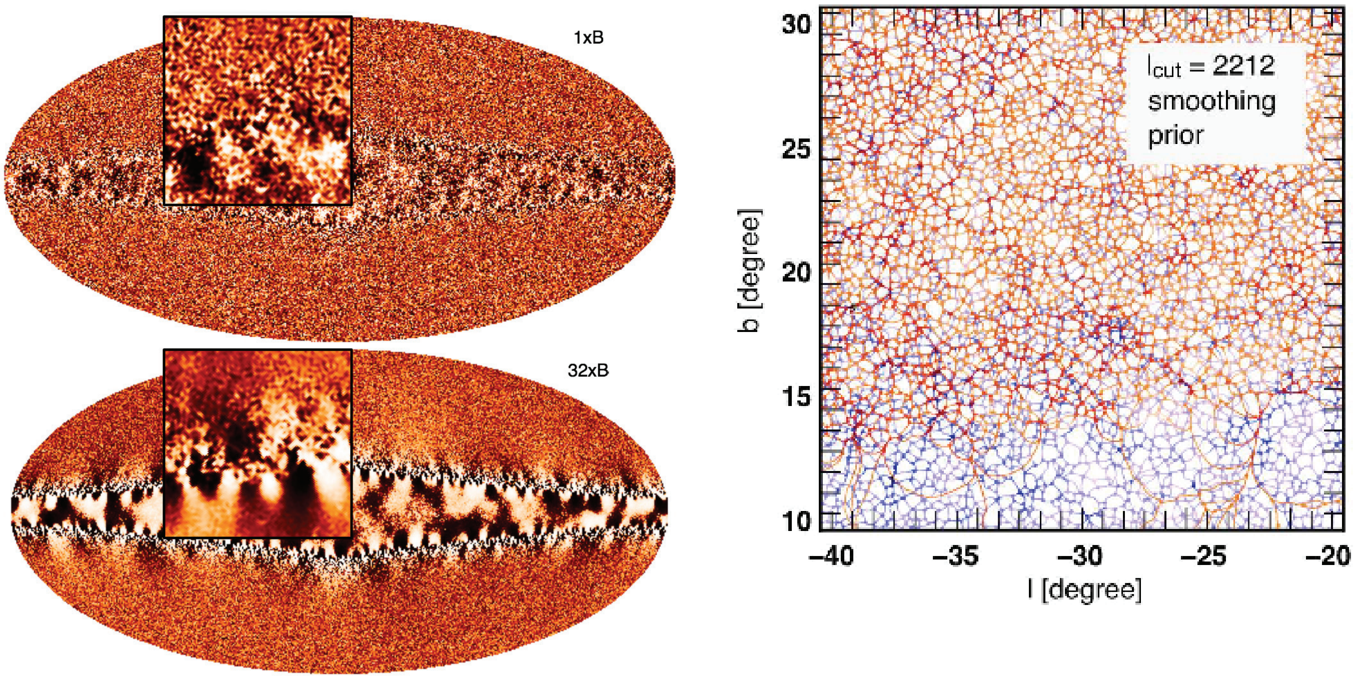


Figure 5.7. *left: an illustration of leaking B modes induced by galactic masks when cosmic convergence is inverted throughout the sky;*

right: the reconstructed skeleton (in red) near the mask (to be contrasted to the "true" skeleton in blue). These virtual data were produced with 4π simulation.

5.3 Probing Large-Scale Structure with Photometric and Spectroscopic Surveys

Two complementary topics have been addressed: to understand the evolution of the large structures and its relation with the dark matter density, and to study the Universe at intermediate redshifts, at the peak of star formation and assembly of galaxies.

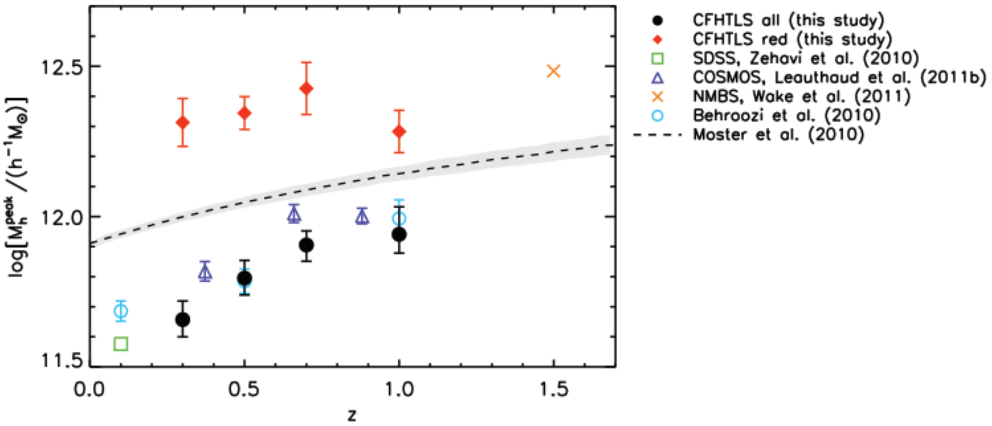


Figure 5.8. *Mass of dark matter halos at peak star formation efficiency. Black dots are for all CFHT-LS galaxies, red dots for red galaxies in the CFHT-LS. At high redshift, strong star formation occurred in more massive halos.*

The clustering of galaxies is linked with their formation process. Mc Cracken et al (2008) has used photometric redshifts to study the evolution of the clustering of galaxies with time based on the 4 deep fields of the CFHT-LS. The accuracy of these measurements had been compared to the results of spectroscopic surveys on smaller field. For intermediate luminosities, the intrinsic colors are more correlated with clustering properties than the absolute luminosity. This confirms the importance of environmental effect in the evolution of galaxies. Several limitations weakened this work. The first was the size of the fields, which remain too small to cover a wide range in luminosity. Photometric redshifts have been computed for all the galaxies of the CFHT-LS (see Figure 5.8). They are now publicly available (Coupon et al, 2009). Second, a new implementation of the analytic halo model has been developed to better analyze the size of the dark matter halos hosting the galaxies. In this model, the number of galaxies inside a halo depends only of the halo mass (see Cooray and Seth, 2002, for a review). From this hypothesis, it is possible to predict the clustering of galaxy selected by mass in function of their redshift and their luminosity. Comparison between the observation and the prediction of the model gives the mass of the halo hosting the galaxies. In the local Universe, the efficiency of star formation depends on the halo mass, with peak efficiency for halo mass at 1010 solar masses. How this property evolved with redshift ? From the clustering properties of the CFHT-LS redshift catalog, it has been possible to demonstrate that halo mass corresponding to the peak star formation efficiency slowly decreases with redshift, with low values at low redshift (Coupon et al, 2009). This work provides also the best determination of the evolution of the galaxy bias factor and the dependence of the clustering properties of galaxies with their colors and luminosity at half the age of the Universe, extending the local results of the Sloan Digital Survey to high redshift.

The lack of infrared measurements for the CFHT-LS prevents to determine intermediate redshifts (1 to 3) where star formation and clustering were at their maximum. This has been done for the COSMOS 2 deg2 field. TERAPIX has been highly associated in the processing of the COSMOS data, with, in particular the U* and K bands obtained with MEGACAM and WIRCAM on the CFHT. With a depth at magnitude KAB ≈ 23, the WIRCAM observations of the COSMOS field were the deepest and widest survey in the near infrared (Mc Cracken et al, 2010). These analysis has shown that massive elliptical galaxies were already formed at intermediate redshifts and that most of the subsequent evolution of the global mass function takes place in the low mass part of the mass function (Ilbert et al. 2010).

Large progress has been done to add infrared data to the CFHT-LS. Thanks to an ANR grant, (Désir, PI. J.P. Kneib, and H. Mc Cracken for the TERAPIX part), a post-doc, has been hired (2008 – 2010) to analyze all the JHK data existing for the CFHT-LS deep fields (Bielby et al, 2011). This has led to the discovery of several high redshift clusters of galaxies, providing a test independent of the halo model developed previously (Bielby et al, 2010). The next step will come from the VISTA telescope, and in particular the UltraVISTA survey, with a capability to detect fainter galaxies at higher redshifts on the COSMOS field. The expected depth is two to four time fainter than for the CFHT-LS. Thanks to these new observations all the analysis done for z ≈ 1 with the CFHT-LS will be pushed to z ≈ 2 with the UltraVISTA survey. The duration of the survey should be 5 years. The first year observations has been processed and delivered to the consortium by TERAPIX at the end of 2010. The pipeline developed for WIRCAM has been successfully adapted for VISTA, keeping the capability to determine a very accurate background level, and to use distributed computer clusters. This is a unique feature of the TERAPIX pipeline. These data will become public and available through the ESO archive soon.

5.4 Probing Dark Matter Halos with Strong Gravitational Lenses

Strong gravitational lenses provide a unique tool to detect mass condensation in the Universe like galaxies and cluster of galaxies. The ultimate goal is to reconstruct the dark matter distribution. Using the CFHT-LS multi-wavelengths images and new analysis methods, Gavazzi et al (2007, 2008) have built the largest sample of strong lenses at intermediate redshift, z≈0.6 (see Figure 5.9). This project is known as the SL2S.

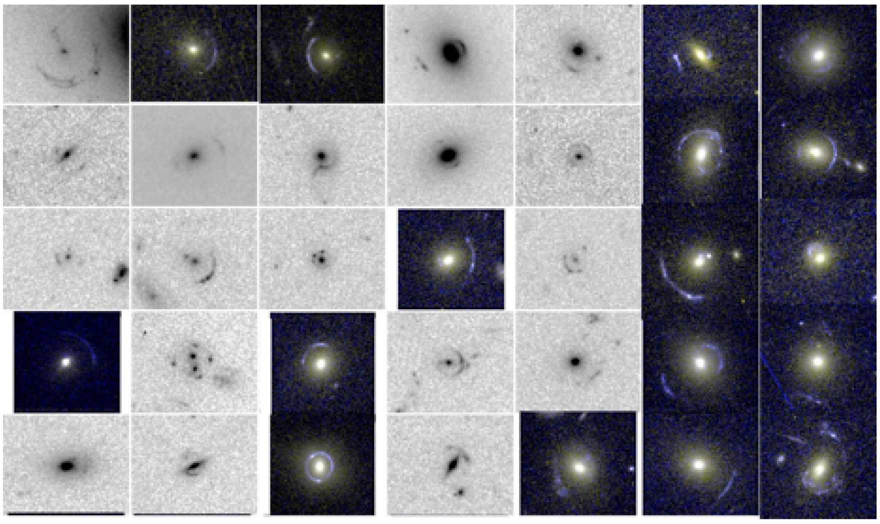


Figure 5.9. *Gallery of gravitational lenses discovered in the CFHT-LS images, and confirmed by HST images, and detailed modeling.*

The new algorithm of automatic detection of gravitational arcs has been developed by C. Alard (2006). It is based on the computation of an optimal estimator of local elongation. Maps of elongation are generated and arcs are identified by connectivity and thresholding. This method has been used for the CFHT-LS analysis (Cabanac et al, 2007, More et al, 2012). After high resolution HST images, the geometry of the lens can be determined, as well as the distribution of dark matter at the origin of the gravitational lens (Limousin et al, 2009, see also Tu et al, 2008, 2009). However, standard techniques cannot get rid of degeneracies, and should be adapted to each configuration. To overcome these difficulties, C. Alard (2007) has developed a new perturbation theory from an initial configuration. In this theory, the strong lenses are represented by a set of non-degenerated quantities providing a general description of the gravitational potential. This new method has been studied for several types of dark matter halos, including ellipticity and sub-structures. Alard (2008) has shown that this method gives a good reconstruction of the images, and allows computing easily the mass distribution parameters, even in the presence of substructures.

This perturbation theory has also been tested with dark matter halos computed in high-resolution numerical simulation (Peirani et al, 2008a, see Figure 5.10). In all cases the image reconstruction is better than 1% in Einstein Radius unit. The efficiency of this method has been demonstrated by its ability to reconstruct 2 real lenses that cannot be done by more conventional methods. The first is a small cluster of galaxies with a complex potential due to the presence of 2 halos, probably the result of a merger (Alard, 2009). The second is due to a single galaxy at the edge of a cluster. The method can easily separate the galaxy specific field from the cluster field outside the Einstein radius of the galaxy (Alard, 2010).

Combined with the SLACS survey of low z lenses based on the SDSS spectroscopic survey, The SL2S has produced the first strong constraints on the slope of the density profile in massive galaxies and on its evolution with redshift. Both projects have benefited from generous time allocation on the Keck telescope and the VLT for spectroscopic measurements, and on the HST for high spatial resolution imaging (Gavazzi, 2008) to confirm the candidates identified in the CFHT-LS images.

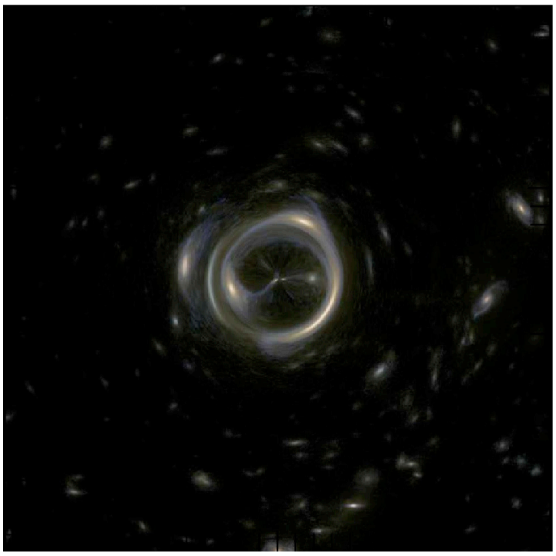


Figure 5.10. *Example of a strong lens from the Mare Nostrum numerical simulation.*

Beyond immediate applications, with the SLACS and SL2S samples, these methods of automatic detection of lenses in wide field images will be of paramount importance for future wider surveys with the LSST and/or EUCLID. A large effort has been done by Raphaël Gavazzi to develop numerical tools that can be implemented easily on different computer networks and for different surveys. These tools will become the building blocks for a future automatic lens detection package.

The observed lenses can be compared to the prediction of numerical simulations to validate physical mechanism included in the hydrodynamic simulations like the prescription for the star formation and the feedback mechanisms. An instrument like MUSE, a second-generation instrument for the VLT, will be the next observational step for combining lensing and dynamical analysis. The Herschel far infrared surveys are another tool to detect strong lenses, at higher redshift (e.g. Omont et al, 2011). Follow up in the mm with IRAM now and later ALMA provides insight in the interstellar matter with line like CO, or H_2O and continuum images of the lensed objects. This is a very promising method for further studies.

5.5 Numerical Cosmology and Galaxy Formation

The research group played a major role in the Horizon project, and more recently in its extension Horizon-UK. The IAP contribution includes the processing and the post-analysis of hydrodynamical simulations with various physical components, Mare Nostrum (1024^3 particles in 50 h^{-1}Mpc, with 4 levels of refinement) (Ocvirk et al., 2008, Devriendt et al., 2010, Pichon et al, 2011) and dark matter only, Horizon 4π (4096^3 particles in 2Gpc/h) (Teyssier et al. 2009, Davis et al. 2011, Le Goff et al. 2011, Codis et al, 2012). The main IAP contributions were the generation of initial conditions (Prunet et al, 2008), the run monitoring, the development and the adaptation for parallel processing of analysis algorithms (e.g. Pownes for multi-scale power spectrum, Colombi et al., 2009), and the production of catalogs of structures and substructures, and finally, the generation of the data base for morphology and photometry of all galaxies generated and the production of associated catalogs of observables, which have been made public (Gay et al, 2010)

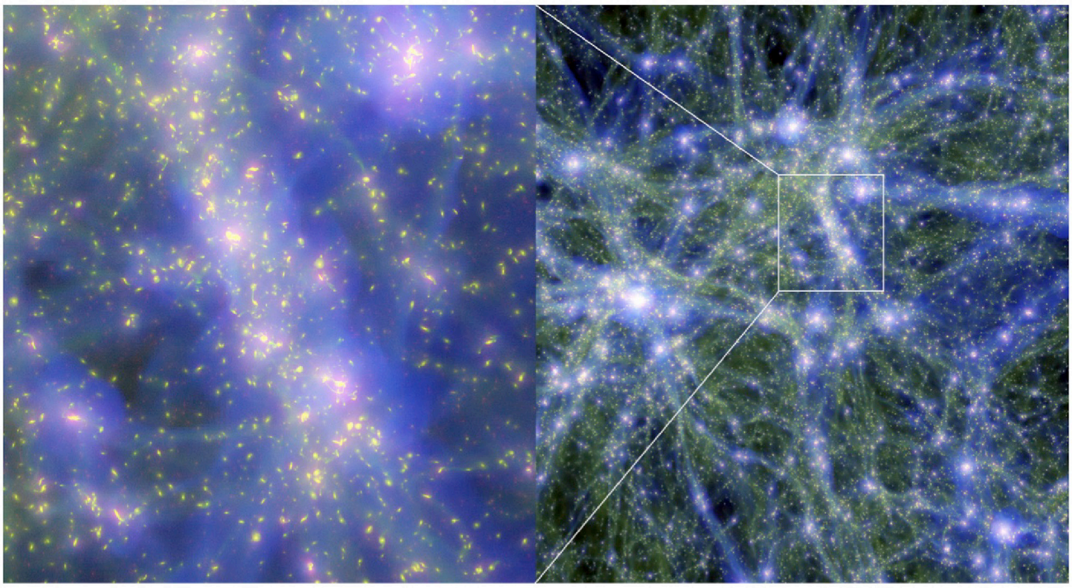


Figure 5.11. *Multi-scale view of the components of the Mare Nostrum simulation at redshift 1.5.The size of the simulation is 50Mpc/h. Zoom on the left side correspond to 10Mpc/h. This simulation includes star formation, metal production and feedback.*

Further analysis of the Mare Nostrum simulation have led to the analysis of the distribution of the different components and to the analysis of the accretion process at virial radius. (Ocvirk, Pichon et Teyssier 2008, Guillet, Teyssier et Colombi 2010). Another product was the study of the luminosity function and its evolution with time (Devriendt et al, 2010).

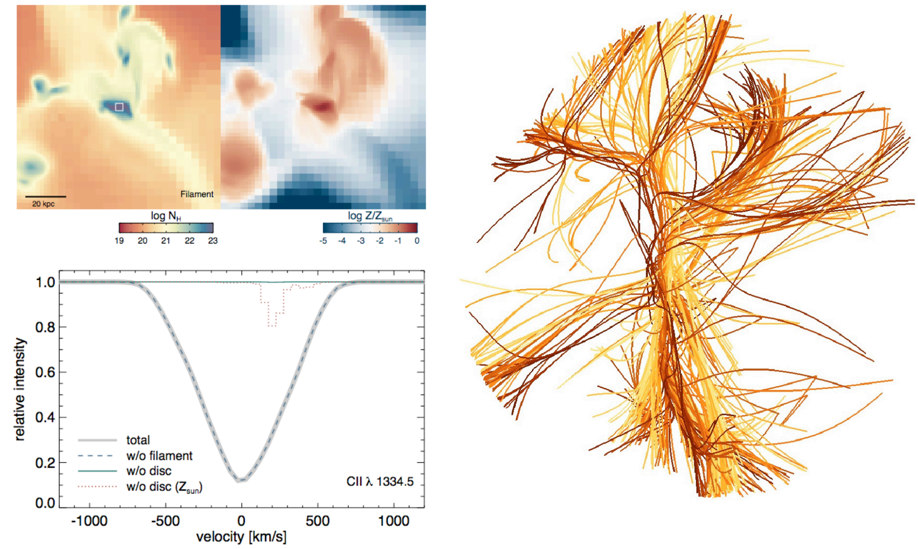


Figure 5.12*. On upper left side, column density and metallicity maps in a filament close to a cluster of galaxies. On the lower side, prediction of the CII 1334.5 A absorption line profile, which show that the filament cannot be detected.*
On the right side, sweeping of filaments centered on a cluster.

5.5.1 Processes of Galaxy Formation in their Environment

The influence of the environment for the morphology of spiral galaxies (spiral structure, warp, thick disk, etc.) is modulated by the susceptibility of each object to react to external perturbations. Numerical cosmology is reaching now accuracy good enough to study such dynamical processes. Realistic models of Milky Way like galaxies have a resolution up to hundred of parsecs. Ocvirck, Pichon and Tessier (2008) have shown statistically that the observed bimodality of the spectro-photometric properties of galaxies could be explained by a negative feedback mechanism for the most massive galaxies at redshift 2. With halos getting more massive, the temperature of the shock-heated gas around galaxies reaches higher values with longer cooling times, and maintain the gas in an adiabatic evolution, this process is able to stop the accretion of cold gas from the filaments, while cold flow accretion on smaller galaxies can continue for a longer period of time. Dekel et al (2009), in a paper published by Nature, have shown that continuous accretion from cold flows is the principal process to sustain a high star formation rate in galaxies at intermediate redshift. UV luminosity function derived from the Mare Nostrum simulation are compatible with the most recent observations, providing one adds a dust model taking into account the metallicity, as predicted by the simulation (Devriendt et al, 2010). The importance of environment for the morphology of the galaxies has been quantified by Gay et al (2010) who have used the distance to the filament skeleton as a metrics (see Figure 5.16 right).

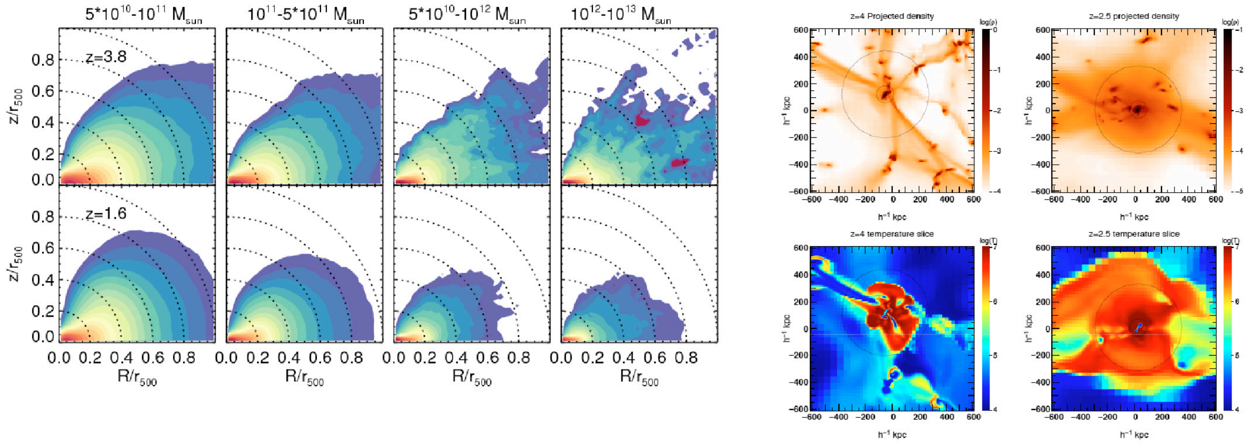


***Figure 5.13**. On the lefts side, averaged over 10 000 halos maps of meridian angular momentum accretion of gas on the halo cores in function of mass of the central object and redshift in the Mare Nostrum simulation. A coherent image emerges between the large scale dynamics and these accretion mechanisms. On the right side, accretion maps at 2 redshifts demonstrating the bimodality in the distribution of shocks.*

According to simulations, these cold flows have a no chance to de detected in absorption, since their cross section is small compared to that of the interstellar medium (Kimm et al, 2011, see Figure 5.12 left). From the statistical analysis of chemo-dynamical accretion maps at the virial radius, Kimm et al (2012, submitted) have suggested a shift of paradigm for the formation of disk galaxies through secondary infall. In this model, the radially stratified angular momentum of the disks follows directly of the residual transverse motion of gas coming from the voids surrounding walls and filaments (Pichon et al, 2011, see Figure 5.14). This inside-out build up of disks arises because the gas shocks isothermally (losing thermal energy through efficient gas cooling) when entering the cosmic web and therefore advects its momentum preferentially along that web. The same mechanism also applies at higher redshift during the rapid formation of the first generation of AGNs, after an initial phase of direct accretion of gas along filaments, the importance of which is litigated by the halo rareness (Dubois et al, 2012). It appears that at high redshift, galactic morphology is mostly driven by the environment.

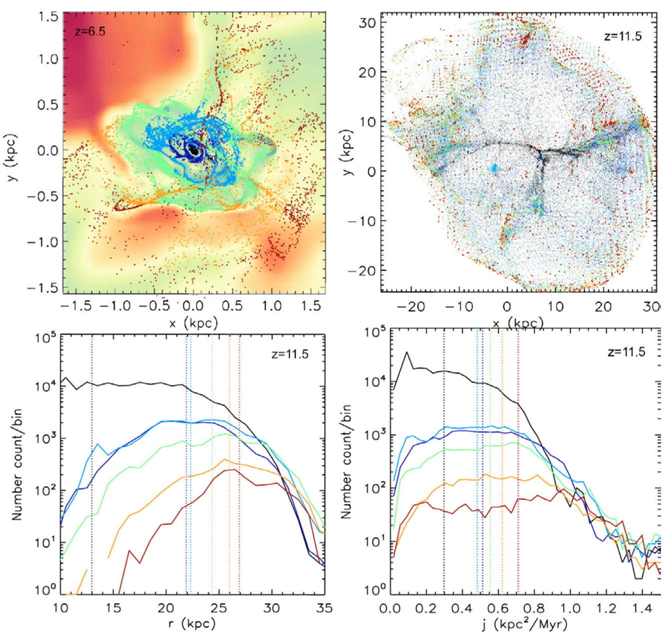


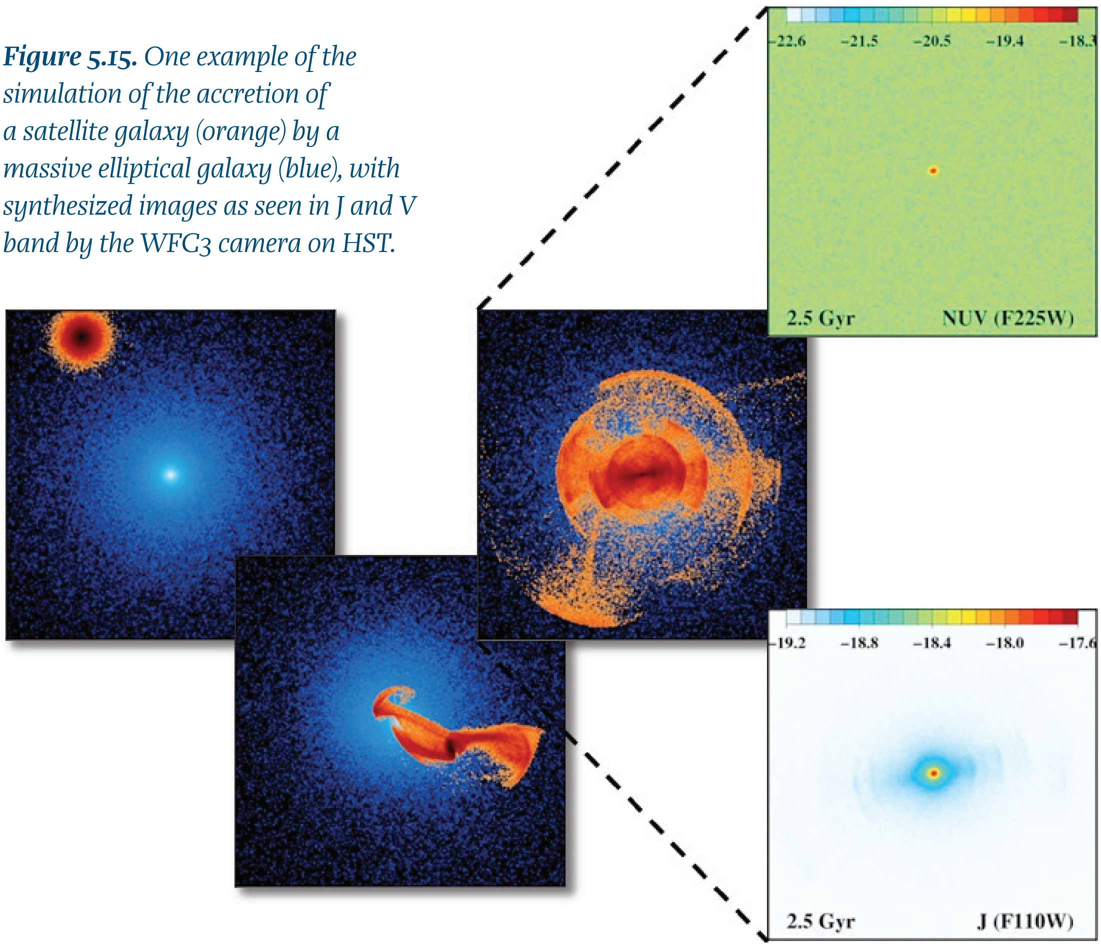
***Figure 5.14.** Validation of the model of stratified accretion of the gas in function of its cosmic origin. .*

5.5.2 From Numerical Halos to Observed Galaxies

Halos are not smooth structure. They have complicated substructures that can be analyzed by their lensing effects, modifying the image morphology. From a numerical modeling of several hundreds of gravitational lenses, Alard, (2007), and Peirani et al (2008a) have made a statistical studies of perturbation due to substructures in the images of gravitational arcs. Consequences for further studies like EUCLID have been drawn.

To tackle the difference between the prediction of the number of substructures and the observed number of dwarf galaxies, Peirani et al (2010 have run several "zoom" hydrodynamical simulations of realistic Local Groups. One of the main outcomes of this study is the prediction of a population of dark halo deprived of stars at z=0., as the result of supernovae and photo-ionization by the first generation of stars. These halos are characterized by a circular velocity smaller that a critical velocity $V_c \approx 35$ km/s, in agreement with prediction of theoretical models. Simulations of merging galaxies have been used to study the evolution of dynamical and photometric properties of galaxies. They have been able to reproduce together the images obtained by the HST and the velocity field determined using GIRAFFE on the VLT for distant galaxies in a redshift range 0.4 – 0.7 (Peirani et al, 2009). These simulations are the clues to understand how these objects are formed and evolved, or in other words, what is the origin of the Hubble sequence.

__Figure 5.15.__ One example of the simulation of the accretion of a satellite galaxy (orange) by a massive elliptical galaxy (blue), with synthesized images as seen in J and V band by the WFC3 camera on HST.



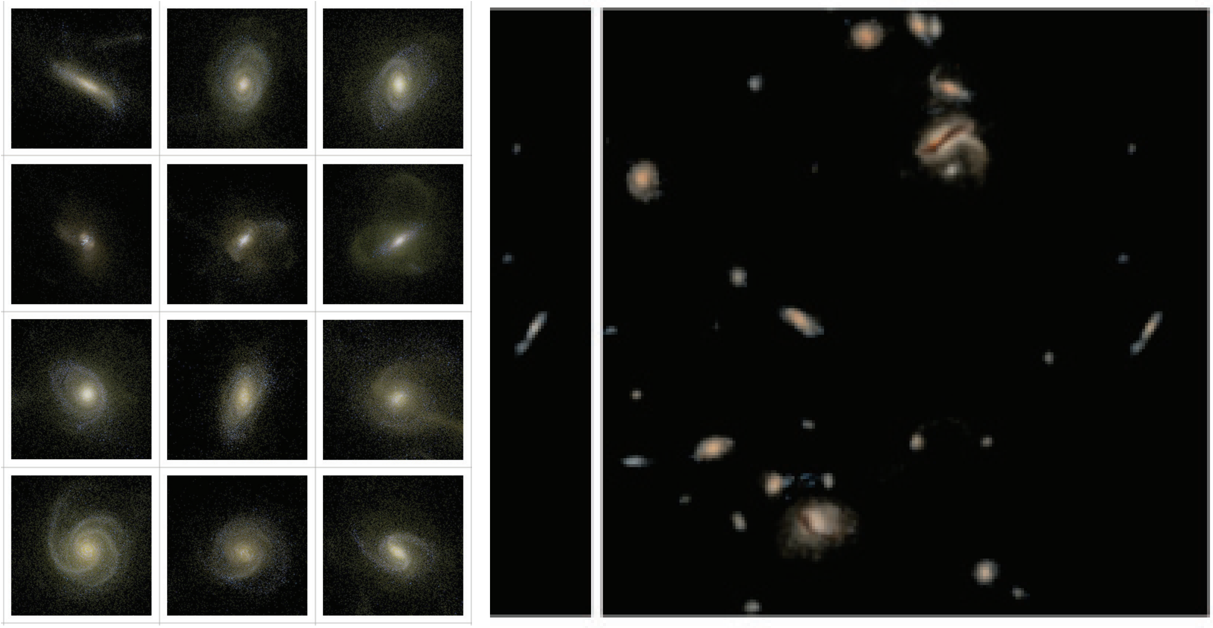


Figure 5.16. *On the left, a field of the Mare Nostrum simulation with (on the right) and without (on the left) post processing of dust. On the right: examples (among 160 000) of galaxies in the Mare Nostrum simulation at z=2.4*

From similar simulations, the star formation of triggered by the accretion of a satellite galaxy on a massive elliptical have been analyzed in details, and synthesized images in different bands (J, H, NUV, Hβ and V) of the WFC3 camera on board of the HST to be compared with the observations (Peirani et al, 2010, see Figure 5.15). These comparisons between synthetic and observed maps can constrain the properties and the ages of these merging events, and by extension the scenario of hierarchical formation of galaxies.

Combining high-resolution measurements in HI and Hα, Alard (2011) has looked at a sample of rotation curve of low surface brightness galaxies. An analysis in principal component has shown that the sample is well described by the first 2 components. The ratio of the 2 components is related to the mass concentration in the center, and therefore to the core radius. This parameter is also linked to the HI gas mass fraction. Hence, the Halo concentration is a fundamental parameter linked with the evolution status of a galaxy, as measured by its gas fraction. Evolved galaxies, with low gas content have a lower central condensation than gas rich galaxies. A possible interpretation of this evolution sequence could be that the supernovae are the agent of gas ejection, but that the evolution itself is due to interaction with the environment.

Using the Mare Nostrum simulation, Guillet, Teyssier and Colombi (2010) have looked at the effect of baryons dynamics on the power spectrum, the variance and the asymmetry of the matter distribution at small scale. They made a fine adjustment by the halo model and included a discussion on weak-lensing effects.

Large-scale velocity fields bring constraints on cosmological models. Lagrangian reconstruction method applied to the observed distribution of galaxies is a possibility to determine such velocity fields. Lavaux et al (2008) made extensive tests the reconstruction method of Monge-Ampère-Kimotovitch (MAK) that they applied to the 2Micro Redshift Survey (2MRS) in the framework of a collaboration with the Institute for Astronomy in Hawaii (Lavaux and Hudson, 2011). In agreement with the results obtained by another research group, they found that the convergence of the velocity of the Local Group toward the dipole of the CMB exhibits a marginal disagreement with the prediction of the concordance model. This will require further studies.

At a much smaller scale, in the interstellar medium of our Galaxy, Thiébaut et al (2010) have identified a possible tomographic reconstruction of the magnetic field from the spectral measurements of the polarization maps. In this context, the spectral dependence of the Faraday length provides a differential probe along the depth direction. It yields a 3D measure of the magnetic field, which allows for a 3D statistical characterization of its properties: topology, helicity, and spectral power. This approach is an innovative non-linear inverse problem of high dimensionality. Polarized radiation transfer in a magnetized medium has been revisited in this new framework (Heyvaerts et al submitted).

5.5.3 Gravitational Dynamics

On large scale, the formation of large structures like filaments, walls or voids is well described by quasi-linear theories: Zeldovitch approximation, perturbation theory ...However, on small scales, the possible stochastic behavior of gravitational dynamics is a source of concern, in particular for simulations of the local Universe. The approach of Thiébaut et al (2008) was to compare Eulerian and Lagrangian quantities computed in a set of N-Bodies numerical simulation, with changes limited to the phases of the initial conditions. At scales smaller than the cluster size, the Lyapunov's exponents increase with the amplitude of the initial fluctuations, for the Lagrangian point of view (characteristic masses) as well as for the Eulerian point of view (characteristics lengths). These exponents measure the exponential growth rate of the dispersion of the observables, in a suite of simulations with only small differences in initial conditions. On those scales, chaos is significant.

5.6 Geometrical and Numerical Analysis of Large-Scale Structures

The topology of the Universe is linked to the geometry of the very large-scale structures. Being homogeneous and isotropic determine the local properties, namely that it is described by a Friedmann-Lemaitre metric. But it does not decides between a topology that could be simply connected or multi-connected. In this later case, the Universe can be seen as a manifold of a smaller volume called the fundamental group. The simplest example is the torus, which is a tilling by parallelepiped of a Euclidian space. Actually, there are more possible topologies than torus. In total, 17 topologies exist for a Euclidian space. And there are an infinite number of possible topologies for spherical or hyperbolic spaces. Topology being a large-scale property, its study requires measurements at the largest scale available for observations, that is the CMB scale. The main impact of topology is to introduce several preferred directions in the Universe: for the torus, the Universe is locally flat, but it is sensitive to the orientation of the fundamental group.

To calculate in multi-connected topology in Euclidian space is rather simple. Eigen modes of the Laplacian are analytic: they are complex exponentials in the case of torus, of various linear combinations of exponential in the other cases. In non-Euclidian spaces, it is much more complicated since the Eigen modes are unknown. In this context, Caillerie et al (2007) have produced the highest resolution images so far of the Poincaré space, which is the most interesting multi-connected spherical space.

Several studies have tried to identify topology that could be detected and how. A new method is based on multipole vectors in which each multipole is associated with a set of non-oriented vectors, and to study their relative directions. Without preferred space direction, the vector directions are all independent, while in presence of a preferred direction imposed by the topology the vector directions are correlated. Bielewicz and Riazuelo (2009) have made an extensive study of mulipole vectors in torus topology. It is important to understand the role of cosmological parameters in the detectability of the topology. Dark energy density increases the horizon size, and then allows studying larger scales. But, more foreground effects, the integrated Sachs-Wolfe effect in particular, affect the CMB map. Kunz et al (2008) have shown that Dark energy has a negative impact on the detectability of the topology, while reionization, also creating foreground effects has no impact on this detectability.

Dark energy signatures on the CMB fluctuations are powerful tools to study the properties of Dark Energy. A. Riazuelo was one of the first to make detailed prediction of CMB anisotropy power spectrum in the framework of quintessence models. Quintessence models are alternate to the cosmological constant since they assume a scalar field producing the dark energy density. The dynamic of the scalar field creates now a very small kinetic term with respect to the potential term. The effect is similar to the cosmological constant since the pressure is almost equal to the inverse of the density.

On somewhat smaller scales, the Cosmic Web is one of the most striking examples of a natural structure. To understand its complexity is difficult, but it of paramount importance because this filament structure still contains signatures of the evolution of Universe since its beginning. In addition, these filaments are the locus of galaxy formation, and their influence on this process remain to be fully understood. The most commonly accepted theory (Bond et al, 1996), the filamentary structure of dark matter is due to the large scale coherence of the initial fluctuation of the density field, amplified by several non-linear gravitational effects increasing the size of the halos by accretion of matters and their fusions.

Sousbie and coworkers (Sousbie et al, 2008, Sousbie, 2011, Sousbie, Pichon and Kawahara, 2011, see fig 5.17) have developed an innovative technique, the skeleton, to characterize the geometry and the topology of the large-scale structure. Formally, the Skeleton is the location where the field gradient is first Eigen vector of its Hessian. This corresponds to ridge lines of the density field. Beyond its interest as a mathematical definition, the skeleton formalism practically allows us to extract and to characterize the filaments via a numerical method based on the intersection of critical surfaces. It has been extensively used to analyze the galaxy distribution in the SDSS. The matter content and geometry of the Universe (total and differential lengths) has been calculated. An Alcock-Paczynski test has been conducted to constrain the curvature parameters and the energy content of the Universe. Dynamical evolution of the filament have been studied (Gay et al, 2010) and linked with the theory of random fields to make a non-Gaussianity test (Pogosyan et al, 2009, Figure 5.18 left, Pogosyan, Gay and Pichon, 2009, see Figure 5.18 right, Pogosyan, Gay and Pichon, 2010)

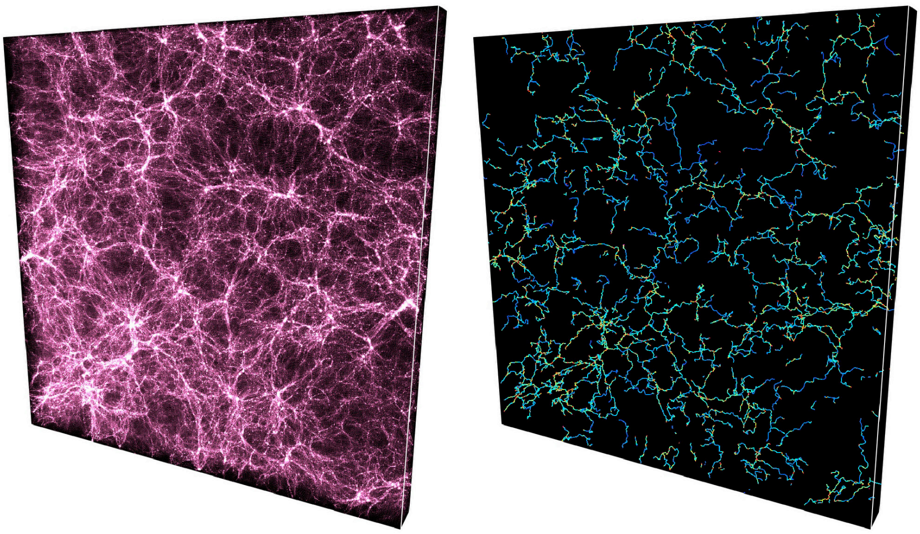


Figure 5.17. *Filament structure in a simulation (left) and 3D skeleton analysis of the structure (right).*

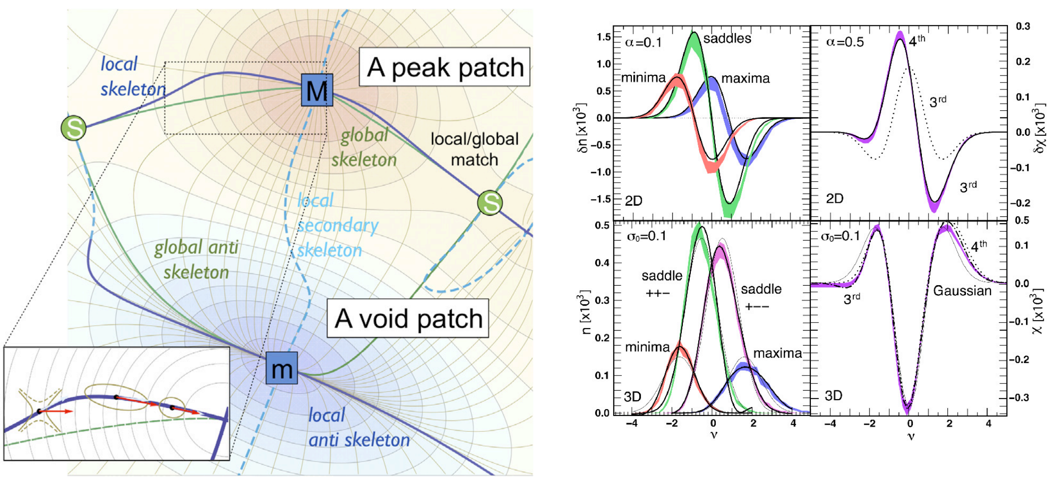


Figure 5.18. *Left, network of critical lines close to a maximum; right non linear evolution of critical points of the field on the left and of Genus on the right, in 2 and 3 D.*

An alterative algorithm, the global skeleton uses a probability propagation scheme to identify the fully connected network of the primary critical lines of the field (Sousbie, Colombi and Pichon, 2009, see Figure 5.19 right). This fully connected skeleton, in contrast to the local skeleton described before, open new possibilities to walk around the cosmic web, to characterize accurately the properties of galaxies as a function of their environment: position in the filaments, distances between halos, anisotropy of the pressure tensor, etc. For instance, Codis et al (2012) have tackled the question of the orientation of the spins of halos relative to the skeleton. The next step is now to extend the skeleton formalism to n-dimensional spaces, n being larger than 3, with two goals: first the characterization of the distribution of matter in the 6D phase space (position, velocity), and the evolution of the matter distribution in time and the skeleton calculated in a 4D space position – smoothing scale related to the skeleton in the 4D space position – time.

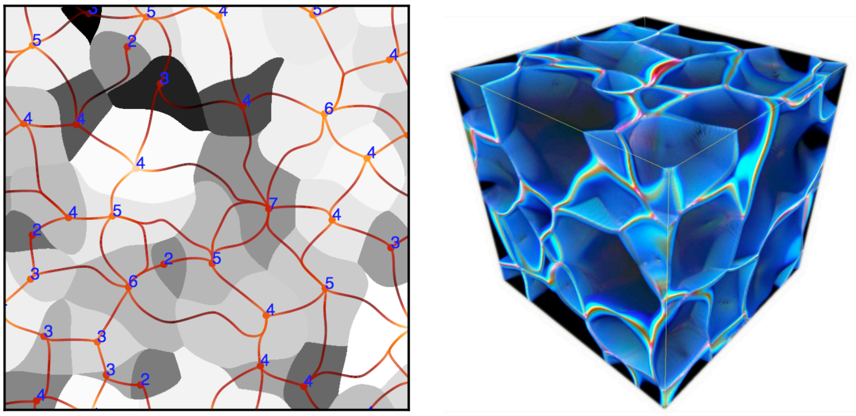


Figure 5.19. *left: connectivity of a 2D Gaussian field on top of the corresponding peak patch segmentation. The geometry of these patches allows us to understand the process of angular momentum acquisition of the central peak.*

right: probability map of the segmentation of a Gaussian field in peak patches.

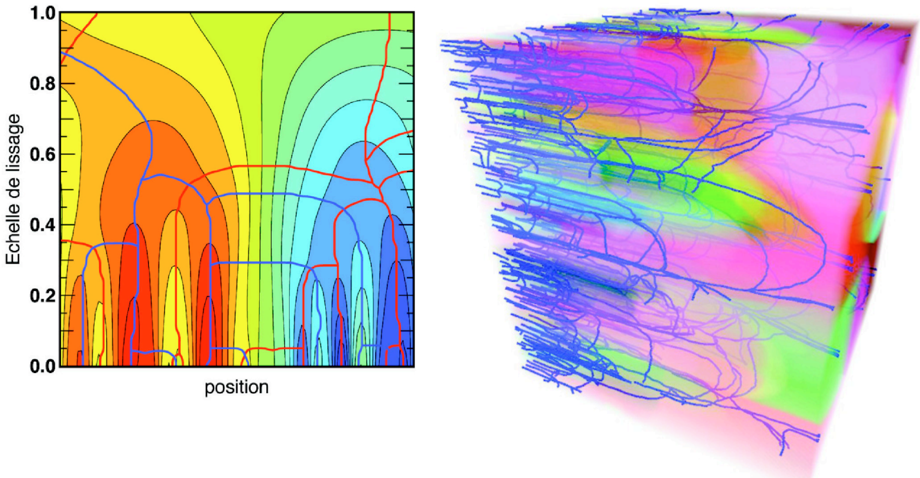


Figure 5.20. *The skeleton (in blue) and anti-skeleton (in red) of a scale invariant 1D (left) et 2D (right) gaussian random field in a position smoothing space, a proxy for space time: such a skeleton represents the time line of halos.*

These sets of tools are crucial ingredients for our investigation of the role of the cosmic environment in shaping galaxies. Pichon et al. (2010) (se Figure 5.19, left panel) have computed the connectivity (the number of filaments connected to a given peak) of the skeleton and shown that the mean degree of a node was a universal property for Gaussian random field. In a cosmic framework when dark energy kicks in, Pogosyan, Gay and Pichon have predicted this decrease via relative counts of critical points of the field. Predicting the evolution of these counts requires expanding moments of the field using perturbation theory (Gay Pichon Pogosyan 2011). This calculation has far reaching implications for studying primordial non-Gaussianities in the large-scale structure of the universe or the cosmic microwave background, in particular since the Euclid mission has now been selected. In this context, Lavaux and Wandelt (2010, 2011) have used voids to extend the characterization of dark energy. These voids can be used as building blocs of purely geometric estimator of the history of the expansion. Specific models of the measured ellipticity distribution of these voids were developed. This line of investigation opens the prospect of precise characterization of dark energy. Beyond these preliminary studies, voids appear promising to extend cosmic probes of dark energy beyond the halo-halo correlation.

Finally, Sousbie 2011; Sousbie & al. 2011 (Figure 5.17) presented the persistent skeleton, which can be implemented directly on discrete sets of particles (such as an observed catalogue or an N body simulation). In contrast to the previous algorithms, noise is automatically taken into account via the mathematical concept of persistence, which relies on a quantitative estimation of the topological features of the catalogue (i.e. how halos, walls, voids are connected to each other). It is therefore straightforward to identify features, which are robust relative to shot noises within poorly sampled catalogues of galaxies in order to compare them to high resolution cosmological simulations. Persistence allows for the extraction of a rigorous, multi-scale, topologically motivated cosmic web (represented by pairs of critical points connected by the network), from large scales structures to cold flows within the core of galaxies (see chapter 7.2.4).

5.7 Phenomenology and Physics of Galaxies in their Cosmic Environment

Supermassive black holes are used by people in the research group as cosmological tools with an emphasis on the black hole formation and its interaction with the host galaxy. Such black holes can be found at redshifst as large as 6, only 1 billion years after the Big Bang. This is hardly compatible with existing theory. New numerical simulations have been performed to identify processes that can explain such a rapid formation (Sadoun Mohayaee and Colin, in preparation).

The motion of a dense object in a diffuse medium creates a gravitational wake, which can reach very large density, depending of the initial conditions. The motion of very distant black holes (redshifts between 10 and 30, as predicted by simulations) in a smooth and diffuse dark matter distribution could reach density large enough to trigger neutralino-neutralino interactions, creating gamma ray emission. This might be observed with the new generation of gamma ray telescopes. Along the same line, Sanderson, Mohayaee and Silk (2012) have analyzed the gamma ray emission by auto-annihilation of dark matter in the tidal tails of M31. The slow velocity of the matter in these caustics results in a significant increase of gamma ray emission compared to the diffuse emission of the halo or to a model with a cross section independent of the velocity. Templates have been computed and adapted to the FERMI observatory capabilities.

Several investigations have been performed to look for local peculiar velocity field. From the UNION2 catalog of 557 type IA supernovae, Mohayaee and Colin (2008) have shown that the acceleration of the expansion exhibits a small anisotropy. Locally, supercluster like the Shapley cluster might have an impact on this acceleration. However, the lack of whole sky coverage prevented to reach conclusion on a possible large-scale anisotropy due to specific dynamical evolution of the Universe. The analysis of the extended Local Group from the Two Micron All-Sky Redshift Survey (2MRS) survey by Lavaux et al (2008, see above) have been extended to look for the coherence of this flow toward the CMB dipole. Most of the amplitude of the CMB dipole is inside a scale of 120 Mpc/h; however its direction is not correct and no convergence can be found at this scale. These results agree with the standard cosmological model at 1-2 sigma only. Colin et al (2011) have checked these results using two supernovae type Ia surveys. Distances from supernovae confirm the lack of orientation coherence, and the agreement with the hierarchical model stays at this level.

Understanding the formation and the evolution of dark matter halos has been an important activity in the research group. For 40 years now, the secondary collapse model was the analytical paradigm in this domain. This model has been extended to non-spherical configuration to study the origin of the universality of dark matter halos. Numerical simulations with different initial conditions have shown that the halos generated have power law density profiles, with an almost constant velocity anisotropy in their central regions. But the index of the power law and the anisotropy amplitude depend on the auto-similarity index of the initial conditions. The halo structure is not universal, but keeps memory of the initial conditions.

The halo model is a well-known tool to study the properties of galaxy clustering as they appear in the observations. The basic assumption of this model is that dark matter halos are the building blocks of the large-scale structures, with galaxies hosted in these halos following a universal profile. In this framework, 3 studies have been performed at IAP, in collaboration with other institutes at the universities of Florida, and Ohio state, and with the CEA: an analytical model on the counting probability, validated par measures in numerical simulation (Fry et al, 2011) and a detailed comparison of the results of pure dark matter simulation with hydrodynamical simulation to seek for a correspondence between dark matter substructures trace galaxies (Weinberg et al, 2008)

The merging of two galaxies with a central black hole is the most probable scenario to explain the activity of AGN. All galaxies have a central black hole, as demonstrated by many observations. In a merging, the binarity of the central engine should be detected, for example via the existence of two peaks in emission lines. However, it is not the common case. A clear signature of binarity can be found in only 1% of the AGN. At $z \leq 0.3$, recent observations have shown that only a small fraction (0.1 to 2.5%) of AGN with a separation of ≈ 1 kpc are binary, which is small compared to the merging rate. Yu et al (2011) have elaborated a phenomenological model to estimate the density of binary AGN. The model takes into account various properties like the gas richness, the size difference of the 2 parent galaxies, and projection effect on the line of sight. They have shown that under certain conditions, the binary AGN rate is compatible with the merging rate, giving more strength to the merging origin of AGN/QSO. One of the predictions of the model is a decrease of binarity with redshift, with only 0.02% to 0.06% of AGN exhibiting double peak narrow emission lines at redshift 0.5 – 1.2.

Dark matter gravitational collapse, halo merging and tidal field of satellite perturbations create thin and dense dark matter shells, also called dark matter caustics. Particles, which might be the dark matter constituent, should suffer large annihilation reaction rate in these caustics, generating gamma rays, anti-protons and positrons. Mohayaee and Salati (2008) have computed that an amplification factor up to 30 can be obtained for the anti-protons of high energy and the positrons of low energy compared to a smooth Navarro, Frenk and White profile. They have estimated the flux on earth of these particles generated in the Milky Way and M31 halos.

5.8 Tools for Image Analysis and Modeling in Large Surveys

As a follow up of the widely use SExtractor free package for automatic photometry (Bertin, 2011), a web site, AstrOmatic.net has been open in 2009. This site contains 10 software packages available to download, including documentation, discussion forum, and space for private and public upgrades. 2000 people are connected every months to this site, with some 1000 downloads. In the last years, these software packages are used and cited in some 3% of the papers published in astronomy/astrophysics worldwide and they are included in the main Linux package (Fedora, Ubuntu, Debian, RedHat, ...). They have been deposited at the Agence de Protection des Programmes (APP) in 2010, and have been valorized thanks to the CNRS Service du Partenariat et de la Valorisation with the Excellence Cluster in Germany, and the Fermi Consortium Alliance in the USA. In 2011, the IAP reward was 10 k€ of royalties.

To have a complete description of image content, we need to have realistic models for the sources, the noise and the PSF. An automatic modeling of the PSF and its spatial variation is now available with the PSFEx package, made public in 2010 (Bertin, 2011), after 10 years of development and testing. It has been used first to perform an automatic evaluation of image quality inside image processing pipelines developed mainly for TERAPIX and Astro-Wise, and has since been used for astrometric and photometric measurements of stellar fields (Bouvier et al, 2008, Delorme et al, 2008, 2010). PSFEx is now used in the analysis of galaxy morphological properties developed for the CFHT-LS and other surveys in the Origin and Evolution of Galaxies research group in IAP (Baillard et al, 2011, Bertin, 2011). PSFEx includes also an experimental module to homogenize PSF between different images. This has been developed in collaboration with the Dark Energy Survey collaboration (Mohr et al, 2008, Darnell et al, 2009). It has been used for the first time in the Blanco Cosmology Survey (e.g. High et al, 2010, Zenteno et al, 2011).

5.9 Outlook

We live exciting times for cosmology; the current and planned experiments are promising a wealth of unprecedented data that will allow to address some of the most difficult questions in cosmology nowadays, among which: the physical conditions at the dawn of time, the nature of the dark energy and its consequences on the destiny of the universe, the complex interactions between the dark matter and baryons and how galaxies form.

It is even more true at IAP, which participate strongly in many of those revolutionary experiments. The Planck satellite, now in orbit and soon to release its first cosmological results, is a great success, as was the CFHTLS survey. The space mission Euclid, which will carry out the next generation of such surveys, was selected by ESA. Not only our group at IAP is critically involved in each step of the preparation and operation and data processing of those experiments, but our expertise extends to the science exploitation of the data collected, modeling the corresponding data sets, and publishing and advertizing well cited papers. Finally, and this is particularly important with such large missions, during the past five years we produced and statistically analyzed the most advanced large scale simulations of the field.

This triple expertise, data processing/modeling/simulation allows our group to continually innovate and position ourselves as the initiators of new scientific themes. One of the examples of such innovation being the emergence of the geometry/morphology studies of the large-scale structure (skeletons, voids). Another being our expertise in cosmo-statistics. The activities of the team will strongly benefit from the "Initative de Cosmologie à Paris" funded by the ERC advanced grant of J. Sik, and the ANR Chaire d'Excellence of B. Wandelt. This will ensure a continuous flow of post-docs and PhD students over the next 5 years, in addition to the support coming from CNES and CNRS for Planck and Euclid.

In the future, our group will continue to carry out the scientific interpretation of data from the deep universe, using state-of the-art techniques to produce and analyze these large observational programs, relying heavily on numerical simulation to validate statistical methods on the corresponding virtual data sets. These quests and expertises are a clear asset to the Institute, at the level of the best international groups. It will be important to continue and make sure that our investment in massive data generation and processing remains compatible with its scientific promotion at the best level.

The main topics of research addressed by our group over the next five years will be the use of large scale structures to probe both the cosmological model (dark matter/dark energy) and build a better understanding on how they give birth and environ galaxies. These goals will involve using the datasets made available by our implication in large mission. In the near future, for example, we will explore the Planck CMB data and in particular its polarization and possible non Gaussian properties.

On a longer term, our group will mine the Euclid data, and in particular the wealth of information contained in the almost full sky weak lensing survey. This strategy will only be possible if we preserve and expand our expertise in each of the required steps that goes from the observation to scientific discoveries, and in particular the data processing (DPC pipelines), statistical analysis and inverse methods and numerical simulations. This will allow us to preserve and take full advantage of our prominent position in state of the art international observation missions, but also to remain leaders in planning of the next generation experiments. In the case of Euclid, for example, our team will both work at the level of the building of the weak lensing survey from the raw data, at the level of simulating the survey with an unprecedented accuracy, and at the exploitation of data using innovative techniques that go beyond the usual analysis of the two point functions of the shear fields.

6

Theoretical Physics – Gravitation & Cosmology

The theoretical physics research team – "Gravitation & Cosmology" consists of:

8 CNRS researchers: Gianfranco Bertone, Luc Blanchet, Gilles Esposito-Farèse, Guillaume Faye, Martin Lemoine, Jérôme Martin, Patrick Peter, Jean-Philippe Uzan

1 lecturer: Dan Israël

Over the period 2007-2011:

6 post-doctoral researchers: Alejandro Bohé, Fabio Iocco, Resmi Lekshmi, Giovanni Marozzi, José-María Martín-García, Alberto Vallinotto

9 PhD students: Émeline Cluzel, Sihem Kalli, Flavien Kiefer, Kumiko Kotera, Alexandre Le Tiec, Marc Lilley, Larissa Lorentz, Sylvain Marsat, Cyril Pitrou

2 prizes were awarded by "la Société Française de Physique 2010" to i) Cyril Pitrou and ii) to Jean-Philippe Uzan (2011, Langevin price)

HDR: 5

Publications: I: 258, II: 54

6.1. General Relativity and Post-Newtonian Expansions

Gravitational recoil of black-hole systems responding to the anisotropic emission of gravitational waves has a potentially important impact. We have computed the gravitational recoil of binary black holes at the 2PN order (Le Tiec & Blanchet 2010a,b). Our expression is valid for the in-spiraling phase preceding the innermost circular orbit (ICO). We have found that the recoil effect is dominated by the next plunge phase, i.e. the phase from the ICO to the merger of the two black-hole horizons.

It is crucial to resort to analytical expressions to model the phase and the amplitude of the signal emitted by compact binary systems with high accuracy. This motivates the computation of the post-Newtonian polarization corrections beyond the 2.5PN order. We have obtained all radiative moments at the 3PN order (Blanchet, Faye, Iyer & Sinha 2008). The quadratic corrections are provided by an algorithm whose implementation at 3PN requires using the Mathematica package xAct (see below). Spin effects must be taken into account in the data analysis of black-hole binaries for VIRGO/LIGO/LISA. At the 2.5PN order, the 1PN relative corrections to the spin-orbit effect must be included. We have extended our computations to the 3PN order (Blanchet, Buonanno & Faye 2011). We have also rewritten the gravitational-wave polarizations at 1.5PN order under a ready-to-use form (Arun et al. 2009).

Identification of coalescing compact binaries requires very accurate wave templates. Two approximation schemes are able to provide them: (i) the post-Newtonian expansion, which describes the in-spiraling phase, in a weak field regime but independently from the mass ratio, and (ii) the self-force approach, allowing an accurate description in the strong field regime, large mass ratio regime. We have achieved an extremely precise comparison between the post-Newtonian and the self-force results in their common domain of validity, i.e. in a weak-field large-mass-ration regime. The post-Newtonian expansion was performed at the 3PN order with some extra logarithmic contributions arising at the 4PN and 5PN orders (Blanchet, Detweiler, Le Tiec & Whiting 2010a,b,c).

Second order perturbation theory constitutes a natural extension to the linear perturbative methods. The general formalism of gauge invariant non-spherically symmetric perturbations in a spherically symmetric background was applied to two problems. The first one concerns the perturbations of a Schwarzschild black hole. We have developed a general approach (Brizuela, Martín García & Tiglio 2009), applied to numerical simulations in Pazos et al. (2010), making use of spectral methods to solve partial differential equations. We have investigated the vibrational frequencies of second order modes, as well as the self-coupling of first order modes at the second order. Next, we have studied the second-order perturbations of a collapsing fluid star (Brizuela et al. 2010).

The absorption spectrum of a scalar-field by a black-hole presents oscillations representing the geometrical cross-section of its photon sphere. These oscillations are computationally expensive to evaluate. By analytic continuation of the indices in the complex plane, we have been able to show that these oscillations can be obtained very precisely from the residues computed at the Regge poles (Décanini, Esposito-Farèse & Folacci 2011). In the high frequency limit, we actually obtain a very simple analytical expression, which keeps the same universal form for all spherical black-holes in arbitrary dimensions.

The Cauchy problem on a characteristic cone is of fundamental interest in general relativity. However, it is much more difficult to tackle than its counterpart on a space-like hyper-surface. After analyzing the example case of Minkowski space-times (Choquet-Bruhat, Chrusciel & Martín García 2009a,b), we carried out a thorough analysis of the structure of the constraint equations (Choquet-Bruhat, Chrusciel & Martín García 2010a, 2011) with extensive use of computer algebra. Then, building on previous results by Cagnac and Dossa, we were able to prove a uniqueness theorem, as well as various existence results for special cases (Choquet-Bruhat, Chrusciel & Martín García 2010b,c,d).

We designed a numerical method of summation for the wave equation with spherical harmonic decompositions (Gundlach, Martín García & Garfinkle 2010). We have generalized the "summation by part" idea, yielding highly stable simulations, to spherical coordinates. From 2008 to 2010, we took an active part in the Mathematica package set xAct (http://www.xact.es), for tensor computer algebra, as:

(1) Module handling arbitrary decompositions of vector spaces and vector bundles into lower-dimensional structures (Faye & Martín García);

(2) Extension to spinor calculus on 4-dimensional Lorentzian space-times (García-Parrado & Martín García), motivated by a work on spinor calculus in 5-dimensional space-times (García-Parrado & Martín García 2009 ; Edgar, García-Parrado & Martín García 2009).

6.2 Theories of Gravitation

We have generalized Christodoulou's proof on existence of naked singularities in the process of collapse of a scalar field to a larger class of matter models, such as Brans-Dicke theory. The situation becomes more complicated and some steps must resort to numerical methods in order to show that the system of equations posses self-similar solutions with appropriate properties (Bedjaoui et al. 2010).

We used scalar-tensor theories to illustrate various aspects of relativistic gravitation in Esposito-Farèse 2011, notably the no-hair theorem for black holes, finite size effects and effacement principle in general relativity. We also took into consideration the latest experimental data to constrain scalar-tensor theories, and we are now analyzing those imposed by recent pulsar timings. Many extensions of general relativity introduce vector fields. We have listed the constraints resulting from the energy positivity condition and the requirement that the Cauchy problem is well-posed (Esposito-Farèse, Pitrou & Uzan 2010). We have shown that some have the property that their vector field is not diluted by the expansion.

The MOND model (Modified Newtonian Dynamics) was proposed as an alternative to dark matter. It can be tested in the solar system with the help of the best available ephemeris (Blanchet & Novak 2011a,b). It is extremely difficult to reproduce this phenomenology in a consistent relativistic field theory. We have made a critical analysis of the existing models (Bruneton & Esposito-Farèse 2007), from both experimental theoretical point of views. One of the best candidates is the tensor-vector-scalar theory (TeVeS), but some freely specifiable function needs to be fine-tuned in order to be compatible with solar system and binary pulsar tests of gravitation.

The TeVeS theory can be simplified thanks to a coupling of the scalar field to the curvature, coming from the Galileon theories (see below), allowing to remove the short-distance effects of the scalar field. It becomes compatible with solar system and binary pulsar tests, without any need of fine-tuning (Babichev, Deffayet & Esposito-Farèse 2011a). We have explored a different way of reproducing the MOND phenomenology in a non-local theory, as predicted by some quantum corrections (Deffayet, Esposito-Farèse & Woodard 2011). We have shown that a purely metric model can also predict a light deflection in agreement with the observed gravitational lensing.

Another approach was investigated in Blanchet & Marsat (2011). It is based on the idea that local Lorentz invariance might be violated at very high energy in a regime of very weak acceleration, below the critical MOND acceleration. This could make it possible to define a renormalizable quantum gravity theory (the so-called Hořava-Lifchitz theory).

In a very different approach (Blanchet 2007a), we demonstrate that MOND phenomenology can be reinterpreted as resulting from a "gravitational polarization" in a medium consisting of gravitational dipoles aligned in the field generated by the ordinary masses. This model, originally non-relativistic, was greatly improved (Blanchet 2007b ; Blanchet & Le Tiec 2008, 2009) and leads to a viable model that cannot be distinguished from dark energy plus standard dark matter (CDM) over cosmological scales, at first perturbative order in a Friedman-Lemaître-Robertson-Walker background space-time.

Scalar field models whose equation depends only on its second derivative, known as "Galileons," are invariant when the scalar gradient is translated by a constant vector. However, in curved space, their interactions lead to equations containing third order derivatives, implying instabilities. We have shown that they may be eliminated by adding some non-minimal couplings to the curvature (Deffayet, Esposito-Farèse & Vikman 2009). This was generalized to arbitrary dimensions (Deffayet, Deser & Esposito-Farèse 2009). We have then demonstrated that this concept could be defined, as well, in curved space of any dimension, for p-forms of arbitrary degree (Deffayet, Deser & Esposito-Farèse 2010).

Branes can be accelerated, which raises the problem of their gravitational radiation corresponding to string loop emissions. It may be studied by considering a brane embedded in a Rindler universe. It can be shown (De Klerk, Murugan & Uzan 2011) that a string suspended from a brane has the same shape as a catenary. The time needed for the string ends to come together can be computed.

The constancy of constants allows us to test the equivalence principle at cosmological scales, see the invited review (Uzan 2011), and conference talks (Uzan 2009, 2010a). Recent years saw the improvement of many experimental and observational constraints. We contributed to it in the domain of big bang nucleosynthesis (Coc et al. 2007) and by proposing a new method (Ekström et al. 2010, Coc et al. 2009) based on the evolution of population III stars, modified by a shift of the Hoyle level.

From a theoretical point of view, we have examined (Coc et al. 2007) the impact of unification theories on coupled variations of constants. Together with the team "Cosmology and High-energy astrophysics," we have obtained the expressions for the gyromagnetic moments in terms of the fundamental constants. From a phenomenological point of view, it was argued that observations on quasar absorption systems suggested a spatial variation of the fine structure constant. We proposed the first model (Olive, Peloso & Uzan 2011) that allows a strictly spatial variation on cosmological scales.

We have shown that the recent reinterpretation by Müller, Peters and Chu of atom interferometry experiments as testing the gravitational redshift is incorrect (Wolf et al. 2010, 2011a,b,c).

6.3 String Theories and Applications

Constructing non-supersymmetric gauge theories by means of string theory demands an understanding of string theory without fermions. This was considered impossible because of the Kutasov and Seiberg theorem. We have shown how to by-pass this by resorting to non-critical non-oriented strings (Israël and Niarchos, 2007b), requiring the new orientifolds (Israël et Niarchos, 2007a). We have obtained the first known perturbatively stable model without fermions, and we then investigated a variant of quantum chromodynamics for which it implies an electric/magnetic duality used to analyze confinement (Armoni et al., 2008). With similar methods, we have studied the world-volume theory on domain walls in super Yang-Mills (Armoni et al. 2009), exhibiting a duality that gives access to strong coupling.

Flux compactifications are currently the best candidates to get phenomenologically realistic models, but they are not well-studied in the case of Heterotic strings. We have shown how to get local models of the latter that are exactly solvable (Carlevaro, Israël & Petroupoulos 2008, Carlevaro & Israël 2009). We are now computing gauge threshold corrections to gauge couplings using them.

Quantum gravity is simpler in 3 dimensions than in 4. A generalization called "topologically massive gravity" allows having dynamical degrees of freedom. The vacua of this theory are warped anti-de-Sitter spaces, for which asymptotic properties are little known. We have studied their embedding into string theory giving in a microscopic realization of their asymptotic symmetries (Detournay et al. 2010).

Dp-branes with opposite charges may annihilate due to the condensation of a tachyonic field. A solution describing the process was only known for coincident branes. We investigated in detail the process when two branes are separated (Israël & Kiefer, 2011). This is more realistic in the case of inflationary models. We have found a family of exact solutions to the system and derived the constraints on the form of the effective action following from their existence.

String theory probes space-time geometry at very short scales differently; for instance, a circle of string length radius is equivalent to a line segment. We have shown, how, in this example, the ambiguity still holds for D-branes (Gaberdiel, Israël, Rabinovici 2008). In Israël 2007, we studied the tachyon decay on two types of D-branes, suffering from a geometric instability and an instability due to the absence of charge respectively, in a strongly curved space-time. When the curvature reaches the string scale, we demonstrated that, both types of D-branes, as well as the boundary states that describe their decay, coincide.

6.4 Astroparticles

Ultra-high energy cosmic rays (UHECR), with energy > 1018 eV, are emitted by extragalactic sources. Their origin remains a mystery, which hinges on two questions: Through which process are these particles accelerated to such energies? Why do we not see astrophysical counterparts in their arrival directions?

Regarding the phenomenology of propagation, we have studied the impact of an inhomogeneous distribution of cosmic magnetic fields on the magnetic horizon effect (Kotera & Lemoine 2008a). We have also proposed an analytical calculation of the angular deflection of UHECRs, accounting for the inhomogeneous distribution of magnetic fields (Kotera & Lemoine 2008b); we have also argued that the reported correlation of arrival directions with nearby AGN most likely reflects a correlation with the large scale structure, in which the UHECR sources camouflage. This issue is further discussed in Lemoine & Waxman (2009). Intervening magnetic fields may distort the observed sky maps, provided the sources are transient phenomena such as gamma-ray bursts (Kalli, Lemoine & Kotera 2011).

If UHECR turn out to be heavy nuclei, the phenomenology is drastically modified (Lemoine 2011). It would be difficult to detect secondary GeV-TeV gamma-ray photons from radiative interactions of UHECR (Kotera, Allard & Lemoine 2011).

Similarly, the anisotropy patterns should be weak due to an increased angular deflection. However, one could test the hypothesis of a heavy composition with such anisotropy patterns as a function of energy (Lemoine & Waxman 2009). As we have argued, the recent anisotropy reported by the Pierre Auger Observatory appears in conflict with this test. A recent paper of the Pierre Auger Collaboration that is dedicated to this test, corroborates our results.

Acceleration to ultra-high energies requires powerful relativistic sources (Lemoine & Waxman 2009). Our group works on the physics of particle acceleration at relativistic shock waves, in collaboration with Guy Pelletier (IPAG). We have expressed the requisite conditions on the downstream microturbulence for successful Fermi acceleration in Pelletier, Lemoine & Marcowith (2009). This study also discusses a relativistic MHD instability upstream of the shock, seeded by the net charge carried by the accelerated particles. We have examined the properties of particle transport in a generic microturbulence in Plotnikov, Pelletier & Lemoine (2011). This field of research has benefited from the development of particle-in-cell (PIC) simulations (Spitkovsky 2008), in good agreement with the conditions expressed in our work. We have studied the microinstabilities that are excited in the upstream unshocked plasma by the accelerated particles, and we have thus determined under which conditions the microturbulence can be excited and the Fermi process initiated (Lemoine & Pelletier 2010). We have generalized these calculations in Lemoine & Pelletier (2011a), accounting for the finite angular dispersion and temperature effects. Our results are summarized in the review Lemoine & Pelletier (2011b). We have applied our model to the calculation of a gamma-ray burst afterglow in a magnetized external medium (Lemoine & Pelletier 2011c). Our model predicts a peculiar light curve, which bears interesting resemblance with some of the gamma-ray burst lightcurves measured by the Swift satellite.

In 2008, the report of a so-called "positron excess" by the PAMELA satellite has triggered a surge of interest for indirect detection of dark matter. Our group has shown, however, that quite exotic dark matter would be required to account for such a signal (Bertone et al. 2008a, Bertone et al. 2008b, Pato et al. 2009). Photons appear more interesting as secondary messengers of dark matter annihilation, since they are not subject to energy losses and deflection. Regarding the direct detection of dark matter, our group has determined the local dark matter density with adequate astronomical data (Iocco et al. 2011).

Using numerical simulations, we have characterized the number of sub-structures that could be seen in gamma rays by the Fermi satellite (Pieri, Bertone & Branchini 2007). We have also studied the anisotropy properties of annihilation radiation in the diffuse gamma-ray background (Fornasa et al. 2009, Taoso et al. 2008). The self-annihilation cross-section of dark matter has also been constrained with temperature and polarization CMB data (Galli et al. 2009, 2011). Similar constraints expected from Planck appear particularly interesting, as discussed in Cirelli et al. (2009).

We have shown that self-annihilating dark matter significantly impacts Population III stars either during proto-stellar collapse (Ripamonti et al. 2009, 2010) or on the main sequence (Taoso et al. 2009). This yields new observables for dark matter that could be reached with next generation instruments, such as JWST (Iocco 2009, Zackrisson et al. 2010a, 2010b). Constraints on the interaction cross-section may also be derived from the impact of dark matter on heat generation in the Earth core (Mack et al. 2007). If dark matter does not self-annihilate, it can aggregate inside stars and modify their structure. Interesting constraints have been derived through the measurement of the solar neutrino flux (Taoso et al. 2010).

Finally, our group has examined scenarios in which the gravitino is the lightest supersymmetric particle. Indirect detection can only occur if R-parity is violated ; in this case, it may be possible to detect gamma-rays from gravitino decay and discriminate it against neutralino annihilation (Bertone et al. 2007). We have also shown that the gravitino becomes a natural dark matter candidate in gauge mediated supersymmetry breaking when the messenger field is a singlet (Lemoine, Moultaka & Jedamzik 2007).

6.5. Cosmology and Fundamental Physics

The existence of a recent acceleration phase in the cosmic expansion seems to be well-established. A cosmological constant is a natural candidate. However, its energy density differs by a factor 10120 from the expected vacuum energy. Another matter component could be responsible for the acceleration, as in quintessence models. It remains to be seen how to incorporate them in a realistic model of particle physics (Brax & Martin 2007). Recently, we studied the coupling of the quintessence field with ordinary matter, in the framework of supergravity. We showed how difficult it is to build a convincing model. Either the symmetry breaking gives a very high mass to the quintessence field or the quintessence-field mass remains weak, implying the existence of a fifth force, violating known constraints. In Brax et al. (2009) we intended to solve the previous problem by using the shift symmetry. However, the presence of shift-symmetry-breaking operators leads to a potential that has a minimum for very small values of the field, thus the model behaves like a cosmological constant. We considered (Brax et Martin 2007) that the quintessence field was a moduli field providing an appropriate potential. Next, we tried to “hide” the interaction between the dark sector and matter using the chameleon effect. In the case of moduli considered in our paper, the chameleon effect exists but is too weak to pass the tests of gravity.

It is possible to obtain constraints on the quintessence potentials by combining the observations of SNIa, of the CMB and of gravitational distortions in the CFHTLS. We have performed a first analysis of the CFHTLS data in order to constrain the dark-energy properties in collaboration with the team "Large-Scale Structures and Deep Universe" (Vallinotto et al. 2007).

In Babichev, Deffayet & Esposito-Farèse 2011a, we have showed that the effects of a scalar field can be screened at short distance via some generalization of the Vainshtein mechanism ("k-mouflage"). Thus we expect in this scheme that no deviation from general relativity can be observed in the solar system. However, we show that one cosmological effect is not erased by this mechanism, namely the time variation of the gravitational constant (Babichev, Deffayet & Esposito-Farèse 2011b).

Cosmic acceleration may also be due to some deviation from general relativity at cosmological scales. A classification of models that account for such an acceleration by universality classes has been suggested (Uzan 2007). This work also proposed the first method of post-ΛCDM parametrization to test general relativity at cosmological scales. A different approach consists in starting from the traceless version of the Einstein equations. This idea has been reviewed and updated in Ellis et al. (2010). The roles of the Copernican principle and of our assumptions on our gravitation theory are detailed in (Uzan 2010).

Simultaneously, various models have been studied in detail to get constraints from cosmological observations, as quintessence (Schimd et al. 2007) and tensor-scalar theories, by extending our analysis to big bang nucleosynthesis (Coc et al. 2009) and quantum corrections to cosmological dynamics (Cembrano et al. 2009). This topic led us to compare the predictions with observations (Schimd et al. 2007). We have also obtained the first indication based on cosmological data only that neutrinos need to be mass-less (Tereno et al. 2009). We have demonstrated that the time drift of cosmological redshifts is a useful piece of information (Uzan, Clarkson et Ellis 2008) and investigated the spectral distortion of CMB anisotropies as a signature of non-linear dynamics (Pitrou, Bernardeau, and Uzan 2010).

The prototype model of inflation is that of a slowly rolling scalar field. It provides a mechanism that explains the origin of cosmological perturbations (Martin 2007). The quantization procedure was generalized to homogeneous, non-isotropic spaces in Pitrou & Uzan (2007) .

String-theory based inflation models provide new aspects. The kinetic term can be of the Dirac-Born-Infeld kind, special case of a larger class called "k-inflation." The predictions of these models has been studied in Lorenz, Martin and Ringeval 2008a and 2008b. In the first work, we computed the spectrum of primordial fluctuations in "k-inflation." We showed that it is necessary to define a new hierarchy of parameters. We applied this formalism to known models of brane inflation, excluding one of them. The second task was to compare this spectrum to the WMAP5 data. We were the first to obtain constraints on the heating temperature from the data (Martin et Ringeval 2010) and to calculate the Bayesian evidence for a number of models (Martin, Ringeval and Trotta 2011). We showed that small field inflation seems to be the model that best fits the WMAP data.

In curvaton models, the differential decay of the inflaton and curvaton may result in isocurvature perturbations of large amplitude (Lemoine, Martin, Petit 2008). In string theory, the moduli fields are excellent curvaton candidates, provided they have high masses during inflation (Lemoine, Martin, Yokoyama 2010), thus constraining their parameter space (Lemoine, Martin, Yokoyama 2009). Post-inflationary dynamics lead to interesting effects. We calculated the level of gravitational waves produced during the phase of (p)reheating (Dufaux et al. 2007) and showed how the quantification of perturbations could take into account such non-linear effects (and Pitrou Uzan 2007). We have shown that disruption of short wavelengths are subject to a parametric instability during preheating (Jedamzik, Lemoine, Martin 2010a) and calculated the spectrum of gravitational waves it produces (Jedamzik, Lemoine, Martin 2010b). It seems within reach of experiments such as DECIGO. A volume published by our group (Lemoine, Martin, Peter 2007) brings together texts on inflation.

The detailed study of density perturbations and gravitational waves has become crucial. The spectrum of gravitational waves produced by the coupling between scalar and tensor modes at second order (Osano et al. 2007) was calculated. We have also shown how the formalism of quantification of perturbations could be generalized to take into account such non-linear effects (Pitrou and Uzan 2007). We proposed the first analytical understanding (Pitrou, Uzan and Bernardeau 2008) of the bispectrum of temperature anisotropies at small scales. This result was confirmed by the analysis of the Boltzmann equation to the second order and its numerical integration (Pitrou, Uzan and Bernardeau 2010). It has resulted in an estimate of the level of non-Gaussianity induced by the non-linear dynamics of gravity. This work is based on an extension of the flat sky formalism (Pitrou, Uzan and Bernardeau 2011) and also showed that there was a particular signature of these effects in the form of a spectral distortion of the spectrum (Pitrou, and Uzan Bernardeau 2010). Meanwhile, we have developed (Pereira, Pitrou, Uzan 2007) a formalism for perturbations in non-isotropic space-times (Bianchi type I). This allowed us to obtain the signature of a primordial anisotropy (Pereira, Pitrou, Uzan 2008). This also allowed us to demonstrate the instability of the Kasner spacetime to linear perturbations (Kofman, Uzan and Pitrou 2011).

We proposed the first observational test of the Copernican principle (Uzan, Clarkson and Ellis 2008) using the temporal drift of cosmological redshifts. We showed (Dunsby et al. 2010) that this would allow a discrimination between cosmological models with observational otherwise identical signatures. This led us to try to understand how the structure of the universe might have emerged from a distribution of points. This requires the development of new cosmological solutions (Uzan, Larena and Ellis, 2010) and ultimately opens up interesting avenues of research (Clarkson et al. 2011).

Despite the successes of inflation, it seems important to build alternative models. In bouncing models, the scale factor passes through a minimum. For this to happen, either the universe must have spherical spatial sections, or there is a fluid of negative energy. In the first case, one must explain why the spatial curvature is so small today. As for the fluid of negative energy, it generates almost uncontrollable instabilities. In the case of a positively curved space containing a scalar field, we determined the conditions making a bounce possible and studied the constraints and possible cosmological consequences of such a classic bounce (Falciano, Lilley and Peter 2008). Subsequently, the spectrum through such a bounce was compared with the WMAP data (Lilley, Lorenz and Clesse 2010). We studied the situation in which the bounce is due to the presence of a fluid of negative energy, calculating the spectrum (Finelli, Peter and Pinto-Neto 2008), ending a controversy. A classical, flat spatial section, bounce is possible either by accepting that the cosmological fluid does not satisfy the condition of zero energy or by modifying the theory of gravitation. The first case we studied was by means of an adaptation of k-essence models, dubbed k-bounce (Abramo and Peter 2007), in which we showed that a curvature was required to pass through the bouncing phase. In the second case, we studied theories of modified gravity designed to avoid singularities (Abramo, Peter and Yasuda 2010); again, the curvature is crucial, although its contribution is independent of the characteristic time scale of the bounce itself, so that the zero curvature limit is well defined.

Quantum cosmology effects can be realized thanks to the Hamiltonian formulation of general relativity (Wheeler-de Witt equation). Based on the interpretation of the Broglie-Bohm wave function, one can produce solutions for a zero curvature Universe, for which a bounce can occur at arbitrary length scale. Perturbation theory can be applied to predict the spectrum of gravitational waves and can be scale invariant if the contraction phase is dominated by dust. So it is possible, though very constrained, to produce cosmological perturbations consistent with observations (Peter, Pinho and Pinto-Neto 2007). In this paradigm no inflation is required (Peter and Pinto-Neto 2008).

The review published by P. Peter (Peter 2008) initiated a renewed interest in cosmic strings. This was the opportunity to consider strings endowed by several currents. We have shown (Lilley, Martin, Peter) that if the coupling were strong enough one condensate plays the role of a large positive effective mass for the others, so that the total number of current condensates in the vortex is decreased. The generalization to non-Abelian currents is difficult. We have studied the case in which the condensate is an SU(2) doublet and observed (Lilley et al. 2010) that the induced currents are either all lightlike, or timelike or spacelike, in which case it is necessary to use an ultra-local approximation with 12 new parameters!

6.6 Outlook

The projects of the GRECO team will continue in the following directions:

- Thermodynamics of binary black holes using post-Newtonian approximation;
- Polarization of gravitational waves at 3.5 PN order for binary black holes with no spin;
- Calculation of the spin-orbit effect to high order post-Newtonian;
- Technique of Regge poles for resummation of the relativistic corrections series;
- Inclusion of recently timed binary pulsars to constrain various alternative theories of gravitation;
- The study of the stability of the Cauchy problem of generalized theories of galileons in curved space, as well as special solutions including spherical symmetry;
- The study of the dynamics of a relativistic shock wave, taking into account the nonlinear interaction between the accelerated particles and the neighborhood of the shock;
- Application of models of particle acceleration in relativistic astrophysical sources;
- The interpretation of the results of Auger angular anisotropies and the combined measurement of the chemical composition of cosmic rays of ultra-high energy;
- The growth of perturbations in the model of bounces and associated nonlinear effects;
- Models based on non-isotropic universe, at least for a limited period of time;
- Effect of extra dimensions on the equation of state of cosmic strings;
- Microscopic description of string compactifications with flux;
- Study of tachyons of a multi-branes in string field theory with boundary.

Projects

7

7.1 Transversal Projects

7.1.1 Initiative in Cosmology and Astroparticle Physics at IAP (ICAP@IAP)

In October 2011 IAP established the Initiative in Cosmology and Astroparticle Physics at IAP (ICAP@IAP) under the joint direction of Professors Benjamin D. Wandelt and Joseph Silk.

ICAP@IAP will serve as a collaborative space for path-breaking studies of the cosmic origin, dark matter and dark energy and the evolution of cosmic structures from their seeds until today. The initiative creates opportunities at IAP for astrophysicists and cosmologists in the early stages of their research careers to work with the project directors and other IAP members, collaborators, and visitors for periods of 2 to 5 years.

The initiative is tightly integrated with the activities of the IAP in the areas of: dark matter and dark energy research; ongoing projects to characterize the statistics of the initial universe using Cosmic Microwave Background data from the Planck mission; and ongoing and upcoming large surveys of the large scale structure of the Universe such as BOSS, CFHTLS and the Euclid space mission, recently selected for construction by ESA.

The main sources of funding for this new initiative are Wandelt's senior Chaire d'Excellence in Cosmostatistics, awarded by the Agence Nationale de Recherche in 2010, and Silk's senior European Research Council Award entitled "Dark Matters." Additional funding is provided through the Chaire International held by Wandelt at the Université Pierre et Marie Curie and his associated research projects funded by the US National Science Foundation at the University of Illinois (NSF AST-0908902), an award by the Alexander von Humboldt Foundation in Germany, and Silk's 2011 Balzan Foundation award.

Current project members at the postdoctoral level are Anna Mangilli, Silvia Galli, Yohan Dubois, Alexander Belikov, Gilles Vertongen, Paul Sutter (associated researcher at IAP and postdoc at Illinois) and Jens Jasche (from January 2012). They are joined by thesis students Alice Pisani and Flavien Vansyngel.

7.1.2 Institut Lagrange de Paris: A New International Center for Theoretical Cosmology and High Energy Physics

In the framework of the "French Initiatives d'Avenir" supported by the French Ministry of Universities and research, the proposal led by the Institut d'Astrophysique de Paris, in collaboration with several other Paris laboratories to create a Laboratoire d'Excellence, the "Institut Lagrange de Paris" (ILP) has been successful. The main aim for the Institut Lagrange de Paris is to enable research leading to transformative insights into the three central open questions for cosmology and fundamental physics:

1) What was the physics of the Beginning?

2) What is the physics of the dominant constituents of the Universe, described through the placeholder terms "dark matter" and "dark energy?"

3) How do we understand the non-linear dynamics and evolution of structures in the Universe from cosmic origin to cosmic fate?

Establishing the ILP will:

- Combine existing and internationally recognized research excellence of the member laboratories in theoretical and experimental particle physics; mathematics; astrophysics; theoretical, computational and observational cosmology; computer simulation; and statistical data analysis.
- Create a stimulating, attractive, synergistic, cross-disciplinary and internationally visible research environment through:
    - Targeted seed funding of cross-disciplinary collaborative projects, such as joint theses, and joint ILP postdocs in research areas with transformative potential.
    - Running of ILP collaboration meetings and workshops, and an annual international ILP conference.
    - Maintaining a vibrant short-term visitor program inviting national and international experts and visiting professors, building on the strength of existing interactions with the international scientific community.
    - Synthetic, cross-disciplinary activities such as joint preparation of Physics Reports on the state of dark energy physics, dark matter physics and the cosmic initial conditions by 2015, after the Planck data, and a significant fraction of LHC data, as well as the next generation of large scale structure surveys have become available.
    - Creating six Lagrange prizes inviting globally outstanding researchers and their groups to conduct research in Paris for a period between 6 months and a year.
- Integrate a wide range of expertise, skills, ideas, and novel approaches from across the relevant disciplines.

The ILP goal is to create meaningful and fruitful collaborations across the member institutes expanding upon what has been originated and can be achieved through bilateral collaborations. Examples of target areas for ILP joint projects and research initiatives are:

- Connecting string theory to new observational and experimental constraints.
- Using cosmic microwave background and large-scale structure observations to get insight into inflation and the underlying theoretical framework of the cosmic beginning.
- Jointly analyzing cosmological observations and particle physics data to home in on the nature of dark matter.
- Searching for signatures of physics beyond the standard models of particle physics and cosmology.
- Exploiting new mathematical approaches and numerical techniques to advance our understanding of the gravitational evolution of cosmic structures.
- Creating innovative approaches to large-scale numerical simulations, analysis of large databases and statistical analysis relevant to the science themes of the ILP.

The time is ripe for these and other advances described in our science case. ILP teams have already advanced leading theoretical ideas, new computational methods and data analysis approaches, and privileged access to data from the great international projects of the coming decade, such as the Planck

space mission revealing the primordial, quantum seeds of cosmic structure, the Large Hadron Collider at CERN probing beyond the Standard Model of particle physics, and the first astronomical surveys reaching across large fractions of the observable Universe and across cosmic time. Creating the ILP recognizes the remarkable concentration of expertise in the above-mentioned disciplines at its member laboratories, all affiliated with University Pierre et Marie Curie , Paris 6 (UPMC):

- the Institut d'Astrophysique de Paris (IAP), UPMC and CNRS UMR 7095,
- the Laboratoire de Physique Nucléaire et des Hautes Energies (LPNHE), UPMC, UPD and CNRS UMR 7585
- the Laboratoire de Physique Théorique et des Hautes Energies (LPTHE), UPMC and CNRS UMR 7589

Indeed, the core of the Institut Lagrange de Paris is based on these three laboratories of the University Pierre and Marie Curie (UPMC, Paris 6), associated with the CNRS.

Two other institutions have a special role in our proposal:

- the Fédération de Recherche Interactions Fondamentales (FRIF)
- the Institut Henri Poincaré (IHP)

The Fédération de Recherche Interactions Fondamentales (FRIF) was created in 2005, to foster collaboration between the LPTHE, the LPNHE, and the Laboratoire de Physique Théorique of ENS (LPTENS).

The Institut Henri Poincaré is a strong component of our project with its capability to host schools and workshops in addition to provide meeting rooms and auditoria. Some of the topical schools, workshops and colloquia organized by the ILP will take place in the IHP. Moreover, the ILP, will follow the IHP internal program of schools to develop collaborations with scientists at the borders of ILP's direct interests.

Also associated with the ILP are teams from:

- The Laboratoire d'Etude du Rayonnement et de la Matière en Astrophysique (part of LERMA, Observatoire de Paris, UPMC and CNRS): team leader: Françoise Combes
- The Collège de France, Chaire de Particules Elémentaires, Gravitation et Cosmologie, Pr. GabrieleVeneziano

The unique breadth of expertise united in ILP will provide us with the opportunity to create truly synthetic work, such as assessments of the state of dark energy physics, dark matter physics and our view of the cosmic initial conditions which will result in 2015 when the Planck data, a significant fraction of the data from CERN's Large Hadron Collider and the next generation of surveys of the large scale structure of the Universe will have become available to the ILP teams.

The ILP will train the next generation of leaders in this field through the creation of the ILP doctorate fellows program and enhancing the existing masters courses with an international masters program in fundamental physics and cosmology open to French and international students. These initiatives, combined with a program of yearly international summer schools, are designed to make Paris the destination of choice for the most talented students of the physics of the Universe worldwide.

Fundamental physics and cosmology attract a wide audience in the public arena. A broad array of outreach programs will communicate the fundamental nature of the questions asked by ILP and the wide variety of approaches its member teams pursue to answer them.

The successful implementation of the long term vision supported by a 10-year funding plan will establish the ILP as an internationally visible center of excellence. In the long term, it might be looked at the possibility to convert ILP into a permanent UPMC and CNRS institution with the goal of

creating a lasting contribution to the international research landscape of cosmology and fundamental physics.

Organization

The organization and the management of the ILP should remain simple, while it should obey two boundary limits directed first to the ILP itself, and to the existing laboratories in second. For the ILP, it must be scientifically driven, efficient to support all activities of the ILP and flexible to follow the evolution of the Center. For the existing laboratories, it must maintain a clear distinction between the ILP activities and the existing laboratories. Even if a large fraction (from 50% to 80%) of the activities of the laboratories are encompassed in the ILP, they cannot be reduced to their participation in the ILP. They should be able to define their own strategy and to keep strong priorities outside the main stream of the ILP. The management structure proposed is therefore articulated with a Steering Committee with participation of all share-holders plus external members, a Director and a Deputy Director and a Scientific Committee.

Steering Committee

The Steering Committee ex-officio members are:

- The UPMC President or his delegate
- The CNRS President or his delegate
- The directors or their delegates of the main laboratories involved in the ILP: IAP, LPNHE, LPTHE, FRIF, IHP

There are 7 external members, each of them nominated by one ex-officio member. External members are nominated for 5 years. The Committee elects its chair among the external members. The Steering Committee will meet at least twice a year. Decisions are taken at the 2/3 majority of present members

The Steering Committee validates the global strategy of the ILP, as presented by the Director. It has in charge the nomination of the Director and of the Director Elect. It approves the provisional annual budget and its execution.

Scientific Committee

The Scientific Committee is composed of:

- 7 members elected among the scientists of the participating laboratories and associated teams.

To keep the process simple, each laboratory and associated team will elect one member among its scientist by an internal procedure, which can be different from one laboratory to the other.

- 7 members designated by the Steering Board.

All mandates are for 5 years. To ensure continuity, members can be renewed once. The chair of the Scientific Committee elects its chair among its members. The chair of the Scientific Committee is invited to the meeting of the Steering Committee.

The Scientific Committee evaluates all the proposals to the ILP. It establishes priorities, and makes recommendation to the Director for the budget allocations.

The Scientific Committee, or ad hoc sub groups are in charge of the selection of applicants for all positions (students, post-docs and visiting scientists) opened in the framework of the ILP. It gives advices on all proposals of workshops and colloquia. It validates the course of study proposed at Master and post-Master level.

The Director

The Director is in charge of the ILP as a whole: scientific, training, outreach and administrative activities. He is assisted by the Director Elect. He/she will be working with a support office for the administrative part under his/her supervision.

The Director and the Director Elect are nominated for **2.5 years** by the Steering Committee. The Director Elect will become the new director after the termination of the Director in charge mandate. This scheme ensures continuity in the ILP management, while keeping the director's mandate short in order to keep the ILP open to new initiatives.

The main charges of the director are:

- The definition of the pluri-annual strategic plan and its presentation to the Steering Committee
- The definition of an annual plan with objectives following recommendation by the Scientific Committee
- The elaboration of the annual budget, and its execution, and the associated documentation for the validation by the Steering Committee
- The definition and the maintenance of indicators useful to assess the activities of the ILP.
- The preparation of the evaluation of the ILP by external agencies
- The representation of the ILP in front of external organism

7.2 Projects (I)

7.2.1 Planck

The Planck ESA satellite aims at providing the final mapping of the CMB temperature anisotropies, and to vastly improve the knowledge of their polarization. This entails sensitivity, resolution, and a control of systematic effects such that all the information that temperature fluctuations encode is indeed extracted.

This project started following our successful answer to the call for proposals made by ESA in November 2012 in order to select the third middle-size mission of its Horizon 2000+ program. The phase A study started in Nov. 1994, and was selected in May 1996 (over the same period, we were also selected for a smaller version of the project, SAMBA, by CNES and we participated in the FIRE proposal which lost to WMAP). We build the consortium aiming at providing the HFI instrument at the heart of Planck between February 1997 and early 1999, when the scientific payload providers for Herschel and Planck were selected. Both satellites were launched from Kourou by an Ariane 5 on the 14th of May 2009. Planck regular survey operations started mid-August 2009, and should last till mid-January 2012, which is about twice longer than the nominal mission duration, the latter was completed in November 2010, once all detectors had seen each sky direction twice (at the detector resolution).

The Planck team leader at IAP, François Bouchet, has been a leader of the project since inception; he is science coordinator and Deputy PI of the HFI consortium, and is also in charge of the data analysis (DPC manager). The "Data Processing Center" (DPC) which he developed, is hosted at IAP. Starting from the time streams of data of the satellite and the ground calibration data, it already produced (summer 2010) a series of 6 all-sky maps on the basis of the first 10 months of data (whose acquisition had been completed less than a month before) (figure 7.1). Further processing of these maps allowed removing their CMB contribution and performing a first analysis of the foreground emissions in the frequency range. These maps reproduced below lead, among other things, to the discovery of 20 new galaxy clusters (later confirmed by X-ray observation from the XMM satellite) via their Sunyaev-Zeldovich effect, to the mapping of the fluctuations of the CIB (Comic Infrared Background from dusty galaxies), of the ISM of our Galaxy (enhancing our understanding of dark gas, of rotating dust grains, etc.) and to the timely delivery of the Planck Early Compact Source catalog (ERCSC) allowing Herschel follow-ups. The ERCSC and Planck early results (25 AA papers) were released to the community in January 2011 and published later that year.

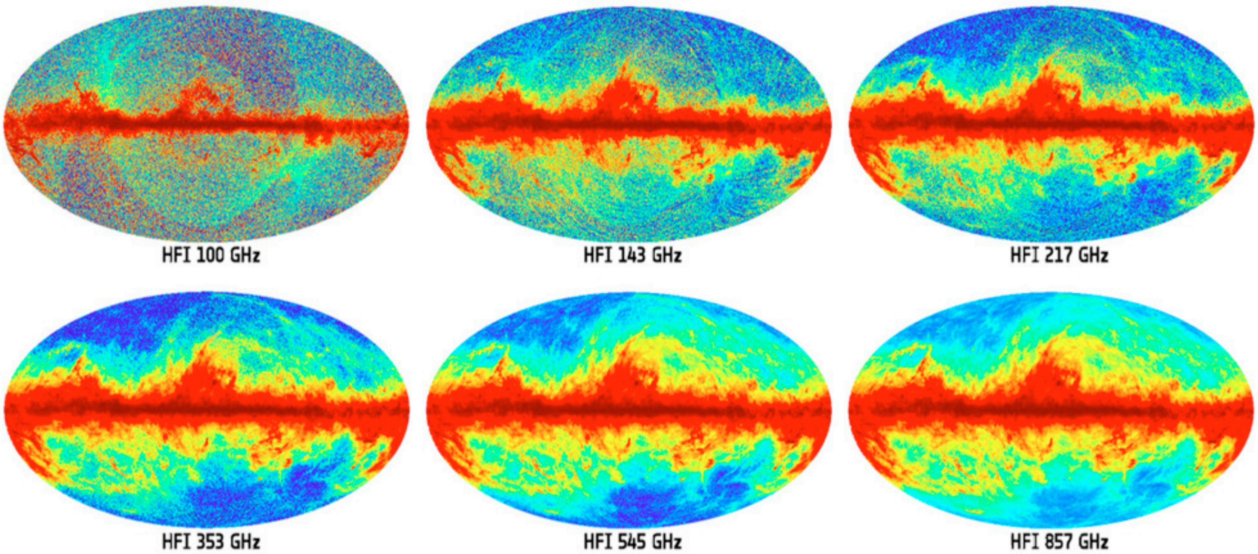
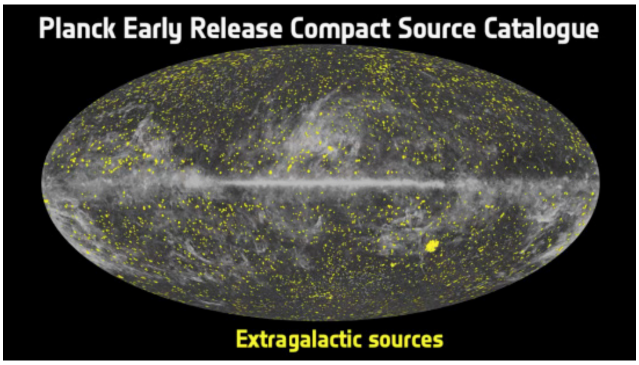
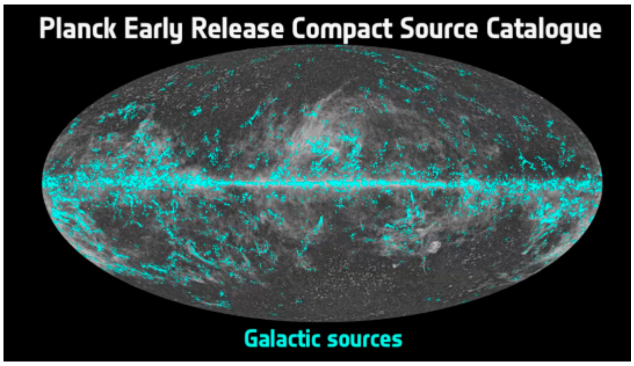


Figure 7.1. *Six Planck cards (10 month data).*





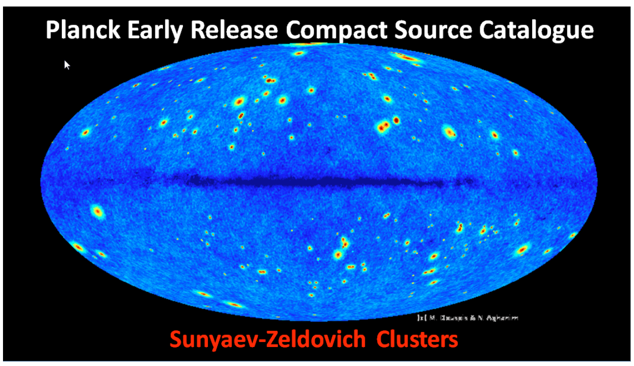


Figure 7.2. *Early Release Compact Source Catalog.*

The DPC then produced (summer 2011) a new set of maps, on the basis of the data from the entire nominal mission, and the first foreground publication appeared in December 2011. At the end of 2012, the DPC will provide ESA with a new set of maps (for distribution to the community shortly afterwards). The goal is that they should be "cosmology grade," i.e. permitting a meaningful analysis of primordial cosmology. We shall also provide maps of the main astrophysical emission mechanisms (including that of the CMB fluctuations, of course), as well as a detailed statistical characterization of the anisotropies (power spectra, likelihood code). A second delivery on the basis of all the data collected by HFI will be made available to the world in early 2014 through the "Planck Legacy Archive" which ESA sets up on the basis of our data, codes and document deliveries. Note that the DPC must also produce intermediate products and releases for the scientific exploitation by the Planck collaboration during the operation, the processing period (one year) and the proprietary period (one year), approximately every 6 months. We have produced 8 internal releases so far. This DPC effort has initially been estimated overall to be about 300 FTEs.

The DPC is geographically distributed, meaning that the algorithmic developments have been distributed between a few countries (France, UK, USA, Germany, Canada) and, within France, to several laboratories (APC, CESR, IAP, IAS, LAL, SAp, LERMA, LPSC). France is responsible for about half of the total analysis effort, on par with its hardware contribution. The IAP team is in charge of coordinating all the data analysis chain (SGS2), while IAS drives the data acquisition and operations (SGS1). The IAP also coordinates the specific French contribution, which concerns the processing of temporal data flows into maps of the sky per frequency. This part of the processing is the heaviest, both in terms of data volume and processing power. Over the years, the IAP team has invested a considerable effort into implementing the hardware and software infrastructure to allow an efficient and traceable processing by the collaboration. The infrastructure we developed was then deployed to additional support centers (CCALI, CPAC, IPAC) to substantially enhance the processing power of the DPC.

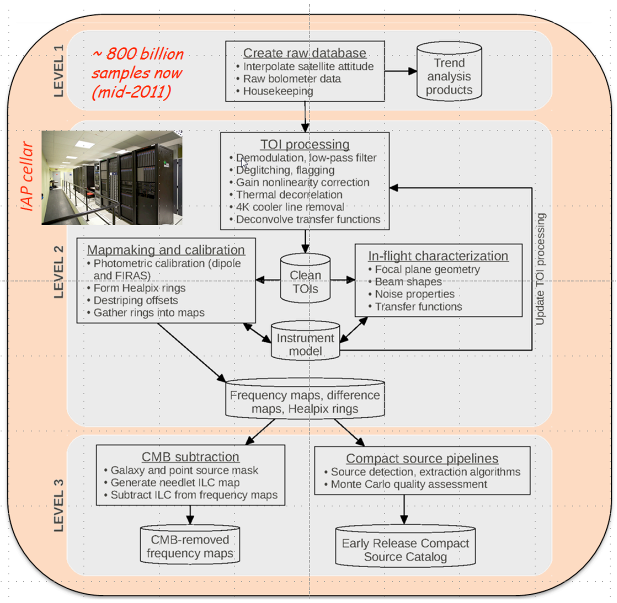


Figure 7.3. *HFI Data processing data flow.*

On the hardware side, the IAP team led in 2008 the specification, acquisition, deployment, and operations of a cluster of 1128 processor cores, with more than 4 Terabytes of RAM, more than 300 Terabytes of fast parallel file system in order to allow processing and analyzing the entire data volume (the machine was at delivery within the top 500 world machines). A dedicated computer room has been designed (thermal and electric specifications), developed and put into operation with the help of the technical and administrative teams of IAP. In 2011, we dimensioned, acquired, and made available an extension of this machine in order to notably increase the capacity of disk storage up to a Petabyte (and an aggregated band pass increase by a factor of 4 to reach 5 Gigabytes per second, sustained). On the software side, the team developed an optimized IO & pipeline & database system which allows tracing (with a web-accessible history) all the operations performed by the data analysis pipelines, while simultaneously allowing manipulating efficiently large data volumes. The team also deployed and operates the collaborative infrastructure of the collaboration (e.g. cvs, cmt, list server, ftp, web, cf. http://www.planck.fr) together with engineers from APC and LAL.

In addition, the team also developed and implemented a number of essential Planck data processing tasks, notably algorithms for characterizing statistically the temporal noise, making maps, characterizing them as well as constructing the detector pointing solution. In all cases, these algorithms have been parallelized in order to best adapt to the hardware computing infrastructure. A number of these algorithms were "battle tested" before their Planck-use in the framework of the Archeops, Boomerang and Bicep experiments, in particular in polarization.

Scientists from the team are involved in scientific projects at the very heart of the primary objectives of the Planck experiment, the very reason indeed of their engagement, and in the development and coordination of the DPC. This in-depth expertise led the collaboration to designate members of the team as coordinators of the following Planck scientific projects: "Temperature and Polarisation Power Spectra and likelihood," "Cosmological Parameters from Planck/CMB data alone," "Non-standard inflationary models," "Cosmic strings and other defects" (while still operating the DPC !).

The IAP team currently consists of 21 people, 8 researchers, 8 engineers (two with temporary contracts), as well as a project assistant and 4 post doctorates. Three theses are on-going.

7.2.2 TERAPIX http://terapix.iap.fr

Y. Goranova (CCD since 2008, 100%), P. Hudelot (CDD since 2008, 90%), F. Magnard (100%), H.J. McCracken (70%), Y. Mellier (PI, 100%), M. Monnerville (100% left IAP in 2011), M. Schultheis (30%), G. Sémah (CDD, 2007-2009, 100%).

TERAPIX is a French national image processing center created in 1998 by CNRS. It aims at providing to the French astronomical community suitable infrastructure and human resources to handle and process big astronomical images obtained with panoramic visible and near infrared imaging instruments, like MegaCam or WIRCam at CFHT, and wide field imaging surveys, like the CFHTLS. Its activities focus on software and pipeline developments for data processing, production of science-ready images and data products, and on technical assistance to astronomers. The center led by Y. Mellier until February 2011 is now led P. Hudelot. The TERAPIX infrastructures and running costs are funded by CNRS (INSU), Paris VI University (UMPC), Cosmology and Galaxy National Program (PNCG) and IAP, which hosts the center. Its computing resources comprise an internal Gigabit Ethernet network, a 40 nodes LINUX cluster with 290 CPUs, and 600 TB of disk space.

Over the 2008-2011 period, TERAPIX focused on the development of new data handling and quality control tools optimized for big mosaic visible and near infrared detectors and for wide field surveys, and on the production of science-ready data for PIs and the CFHTLS, NGVS, VIPERS, WIRDS, WUDS, CFHQSIR, UltraVISTA, VIKING and VIDEO surveys.

Development

TERAPIX developed, integrated and then released to the community worldwide a new tool called YOUPI . It is a portable, easy-to-use web application providing high level functionalities to perform data reduction on FITS images. It is built on top of open source processing tools, in order to organize data on a computer cluster, to manage processing jobs in real time and facilitate teamwork by allowing fine-grain sharing of results and data. All steps of the TERAPIX processing sequences are integrated in YOUPI, from the image ingestion to the control quality of stack images and catalogs. A FITS header conversion module extends its functionalities beyond MegaCam images, to CFHT/WIRCam and ESO/VISTA.

Production

A standard TERAPIX/YOUPI processing sequence comprises 4 steps: (1) image ingestion and data integrity verification, (2) quality control and production of weight-map and flag-map images attached to each input individual image; (3) automated calibration processes and production of stacked images; and (4) monochromatic and panchromatic catalog productions and high level quality controls of images and surveys. This sequence applies to almost all visible and near infrared data sets processed at TERAPIX.

Since 2008, the WIRCam, PI-MegaCam, CFHTLS, and VISTA/(UltraVISTA+VIDEO) projects represent more than 90% of TERAPIX data production activities. Beside the surveys, regarding the PI and Large Programs NVGS, WIRDS, WUDS and CFHQSIR, TERAPIX delivered 51 WIRCam science-ready data packs to 30 different PIs and 30 MegaCam data packs to 23 different PIs.

On the CFHTLS side, during the 2008-2011 period, TERAPIX produced 3 releases

(T0005 in 2008, T0006 in 2009 and T0007 in 2011). The 3 of them have a total of more than 100,000 single MegaCam images, 10,000 stacked images and 3 millions meta-data files (http://terapix.iap.fr/rubrique.php?id_rubrique=259, http://terapix.iap.fr/cplt/T0006 doc.pdf). Each release is complemented by a series of public photometric redshift catalogs, whose production is led by O. Ilbert at LAM (http://terapix.iap.fr/rubrique.php?id_article=830). TERAPIX is also responsible for the production of spectroscopic targets of the VIPERS Large Program on the VLT/VMOS instrument (PI: Guzzo). VIPERS aims at getting spectroscopic redshifts of 100,000 IAB=22.5 CFHTLS color-selected sources extracted from W1, W2 and W4 TERAPIX catalogs. To date, more than 40,000 spectra have already been obtained. Finally, TERAPIX is also in charge of the production of the Large Program CFHQSIR done with WIRCam (PI: Cuby). CFHQSIR covers 130 deg2 of the CFHTLS-Wide in Y, J, H and Ks bands. An early release, aligned with CFHTLS T0006, has been delivered in 2011.

TERAPIX monitors its impact through published refereed scientific papers. From the ADS database, it is acknowledged in 215 articles (http://terapix.iap.fr/article.php?id_article=597), of which 150 have been issued since 2008.

Perspectives: VISTA Public Surveys and Euclid

Since 2009 the involvement of TERAPIX in the image processing of VISTA/VIRCam data and the production ESO/VISTA public surveys are continuously increasing. As a mandatory servicing task, in 2010 and 2011 TERAPIX focused on surveys with French Co-PIs, like UltraVISTA and VIKING. However, after a request for support by the PI, TERAPIX agreed to process also VIDEO data, as a kind of visible added value activity. TERAPIX already released UltraVISTA data to the ESO community and will release VIDEO data in 2012.

On a longer term, TERAPIX plans to have important roles and responsibilities in the science ground segment (SGS) of the Euclid space mission (see the Euclid report). IAP together with the Planck, TERAPIX and Euclid project teams hosted at IAP have started to set up a resource and organization plan in order to smoothly move toward the Euclid SGS activities at IAP.

7.2.3 EUCLID http://www.euclid-ec.org

S. Arduini (CCD CNES , 100%), J.-P. Beaulieu (10%), K. Benabed (10%), J.-M. Delouis (20%), C. Grenet (80%), P. Hudelot (10%), F. Magnard (10%), H.J. McCracken (10%), Y. Mellier (PI, 100%), M. Monnerville (20%, left Euclid in Septembre 2011).

Euclid is an M-Class space mission of the ESA “Cosmic Vision” program that has been selected in October 2011. Euclid aims at understanding the origin of the accelerating expansion of the Universe by using two primary cosmological probes: weak lensing tomography (WL), from shapes and photometric redshifts of galaxies, and galaxy clustering (GC), using Baryon Acoustic Oscillation and Redshift-Space Distortion, from spectroscopic redshifts of galaxies. It will also use clusters of galaxies and the integrated Sachs Wolf effect as secondary probes. Euclid will be launched in 2019 by a Soyuz rocket and sent to L2 for a 6 years mission (http://xxx.lanl.gov/abs/1110.3193). Overall, Euclid is expected to end by 2027.

To achieve its goals, Euclid is equipped with a 1.2 m telescope that feeds 3 instruments covering the same 0.5 deg^2 field of view: a high image quality visible imaging instrument (VIS), equipped with 36 CCDs and a broad (RIZ) filter, a near infrared imaging instrument (NISP) equipped with 16 HgCdTe detectors and 3 near infrared filters (Y, J, H), and a slitless spectrograph equipped with 4 grisms. Euclid will observe 15000 deg^2 of the extragalactic sky, and get the shape and photometry of 2 billion galaxies and the spectroscopic redshifts of 50 millions galaxies. The mission is designed to decisively understand the origin of the acceleration and pin down its nature (dark energy, modified gravity). Euclid photometric and spectroscopic data also have an immense legacy value. They will provide targets for E-ELT and JWST and will perfectly complement Planck, Gaia, e-Rosita or LSST data.

While ESA is responsible for the Euclid mission, a European Euclid Consortium (EC) is in charge of the VIS and NISP instruments and the scientific ground segment (SGS). The EC comprises more than 100 laboratories over 13 countries in Europe, with few laboratories in the US. It is led by the Euclid Consortium Lead (ECL) and a Euclid Consortium Board (ECB). The IAP contributions to Euclid are important and considerably increased in 2011. Its involvement is three-fold; top level management, ground segment and science.

Top Level Management

Since February 2011, Y. Mellier is the ECL. As such he is the single contact point of the consortium with ESA, has the scientific responsibility of the mission and chairs the ECB. Since February he focused on putting the Consortium back on the rails, the demonstration of the feasibility of the mission, its selection (Oct. 4) and its adoption, in June 2012.

As the Euclid top level management has only been recently transferred to IAP and was not planned early on, IAP had to carry out urgent actions which impacted the overall IAP management, TERAPIX, and the Euclid ground segment activities done at IAP. With the help of CNES and CEA, IAP quickly set up a local ECL Support Office (Y. Mellier, S. Arduini, C. Grenet, IAP local support) in charge of completing the Definition Phase and getting Euclid selected. Y. Mellier also set up a Tiger Team in May 2011 which successfully demonstrated the feasibility of the Euclid mission.

Ground Segment

During the 2009-2010 period, C. Grenet and Y. Mellier led the DADA (DArk DAta) project. DADA aimed at defining the organization, infrastructure, and computing resources that the French dark energy community may need to maximize the national scientific return of the Euclid Mission. They succeeded in getting the scientists from INSU, IN2P3, CEA and CNES organized around a single project based on the existing CC-IN2P3 infrastructure. This project was then used in 2011 as the baseline of the French "Science Data Center" (SDC-FR) for the Euclid data processing activities in France.

Between 2009 and February 2011, Y. Mellier was the Ground Segment Scientist of the Euclid SGS activities. Together with the SGS Project Manager F. Pasian, he set the SGS organization and responsibilities, then defined and organized the Euclid data processing tasks into 10 Organization Units (OUs) and 7 Science Data Centers (SDCs).

IAP is responsible for the VIS organization unit (OU-VIS) and in charge of designing and organizing the pipeline and data management of all VIS data. C. Grenet is singly responsible for OU-VIS since Y. Mellier took over the ECL position. She delivered to the SGS Project Office the complete set of OU-VIS documents of the Definition Phase. In addition, J.-M. Delouis, C. Grenet and M. Monnerville contributed to the SGS system activities. They delivered a Euclid data flow simulation tool and participated in the design of the reference logical SGS architecture and in the selection of the data modeling tool. TERAPIX is involved in the OU-VIS and system activities.

Scientific Activities

The Euclid scientific activities carried out at IAP focused on WL (K. Benabed), planets (J.-P. Beaulieu, A. Cassan) and cosmological simulations (S. Colombi). During the Definition Phase (2009-2011), K. Benabed and J.-P. Beaulieu contributed respectively to the organization of the WL and Planet working group activities. IAP scientists participated in the definition of the scientific requirements of the mission, in the prediction of its performances and in the preparation of documents, such as the Red Book.

7.2.4 Numerical Simulations at IAP

The strength of IAP in computer science comes partly from its multidisciplinary approach in three principal fields: cosmology and HORIZON project, (exo)planets and ESINPLE project, high energy astrophysics. Initiated in the past by individual projects, simulation activity at IAP, strengthened by the recent hire of an engineer and a researcher, is now mature enough to compete at the highest international level. IAP has access to national computer resources (IDRIS, CINES, CCRT) and a local hardware configuration comprising 3 32-core machines, a 48-core one and a brand new 64-core computer with 1Tb shared memory, and large disk capacity (about 150Tb). At present, there are no less than eight codes under development or in use at IAP: RAMSES, the public tree-code GADGET, two Vlasov-Poisson solvers, a 3D code of hot Jupiter evaporation, a plasma PM code, a MHD code and a hydrodynamic code to simulate gamma ray bursts.

In cosmology, IAP has participated actively in the improvement of the adaptive mesh refinement cosmological hydrodynamic code RAMSES by developing specific modules: a cooling module (chemical evolution of primordial elements) and a real time light-cone generator. Exploitation of RAMSES within the national HORIZON project allowed us to perform two simulations among the largest in the world (in fact the largest ever at the time of their production): the hydrodynamic simulation of galaxy formation "Mare Nostrum" (Devriendt et al. 2010) and the dark matter simulation Horizon-4P (Teyssier et al. 2009). This latter involves about 70 billion particles in a 2000 h^{-1} Mpc Box! Since 2007, scientific exploitation of these simulations has already led to 15 publications in which IAP is involved (see chapter 5). To generate initial conditions of such "extreme" simulations, the Graphic software (developed by E. Bertschinger) was parallelized under MPI (Prunet et al. 2008) and this parallel version, MPgraphic, has become a standard tool of numerical cosmology.

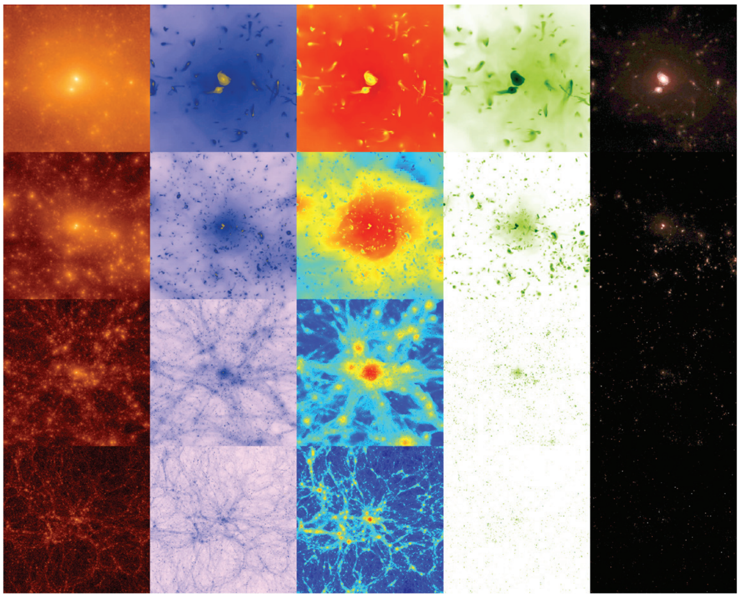


Figure 7.4. *Multiscale view of physical fields in the Mare Nostrum simulation: from left to right, dark matter, gas, gas temperature, metallicity and stars.*

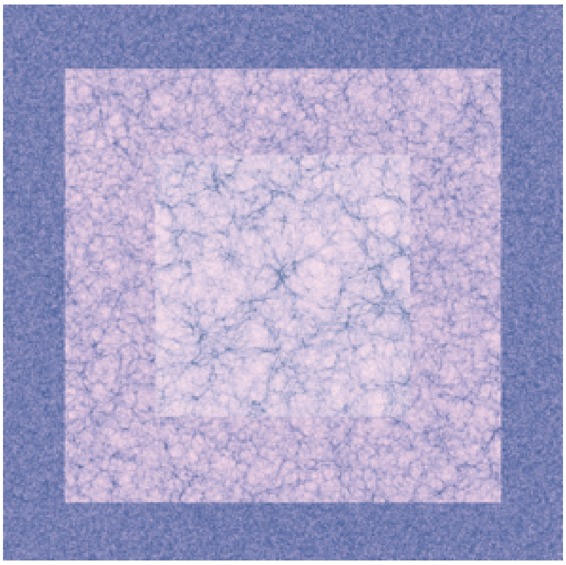


Figure7.5. *Multi-resolution view of the Horizon-4P simulation.*

Beyond the standard use of GADGET2 for generating dark matter simulations, S. Peirani has supplemented this code with a specific star formation model taking into account feedback from SNIa and SNII, metal enrichment as well as UV background due to quasars. By using this customized version of GADGET2, it was in particular possible to study stellar formation processes during galaxy fusions (see chapter 5). In addition, in the framework of his PhD supervised by R. Mohayaee, R. Sadoun has added black holes to GADGET2 and is using the modified code to study super-massive black hole formation at high redshift.

The "zoom" simulation technique is often used in order to study the formation of isolated galaxies or groups of galaxies and IAP possesses an expertise in that field. In particular, high-resolution zoom simulations of a realistic Local Group were performed to study the dark matter substructure distribution as described in chapter 5 and the velocity field of galaxies in the local universe (Peirani 2010), as well as the distribution of baryons.

The Vlasov-Poisson equations, used to simulate the dynamics of dark matter, are usually solved with N-body techniques, which are very noisy in phase-space. One objective is to develop new schemes working directly in phase-space. Colombi & Touma (2008) have examined the traditional "waterbag" method in 1D, spherical systems and disks by following isocontours of the phase-space distribution function using oriented, adaptive polygons. Currently, we are implementing, in the framework of a long-term project, the classical splitting semi-Lagrangian algorithm commonly used in plasma physics.

The team also actively develops tools for the statistical analysis and the detection of structures and substructures in cosmological simulations. Works in this field include:

- Coupling of the adaptahop code of halo and sub-halo detection (Aubert, Pichon & Colombi 2004) with semi-analytic models of galaxy formation applied to N-body simulations (Tweed et al. 2009). The code adaptahop is widely used within the HORIZON project.
- A phase-space sub-structure and structure finder, developed in the framework of the PhD of M. Maciejewski (Maciejewski et al. 2009a, 2009b), that proves to be one of the 2-3 best codes of its kind, as shown by the comparison article by Knebe et al. (2011) in which IAP participated.
- The powmes code which uses a Taylor expansion approach to extract rapidly and with great accuracy the power-spectrum from an N-body simulation over all the available dynamic range (Colombi et al. 2009); this code is already widely used in numerical cosmology.
- A full-sky ray-tracing code on the sphere to treat weak lensing in N-body simulations. This code was already applied to the Horizon-4P simulation to generate a full-sky lensing map (Teyssier et al. 2009).
- A filament detection code in 2D and 3D (Sousbie et al. 2008) using a local approximation of filaments initially suggested by Novikov, Colombi & Dore (2006); an improvement of this code allowing one to draw the actual ridge lines in a smooth field without the presence of noise by combining a probabilistic approach and a percolation algorithm (Sousbie, Colombi & Pichon 2009); finally, a robust algorithm (Sousbie 2011; Sousbie, Pichon & Kawahara 2011) taking into account the noise by relying on the latest developments of discrete topology and the concept of persistence, which allows one to assign to each topological feature of the field (modeled by a critical point pair) a number estimating its

relative importance. It is possible with that procedure to define a threshold below which the corresponding features can be considered as part of the noise. These topological features are then erased with a minimal geometrical transform of the field ending up in a simplification of the critical lines network. The corresponding code, DisPerSE, is now in its final stage of adjustment to become public.

IAP has also developed a unique expertise in the generation of virtual observations. These mock observations are obtained from a sophisticated post-treatment of numerical simulations. Their applications are numerous: deep galaxy surveys, gravitational lenses in the strong or in the weak regime (e.g., Semboloni et al. 2007; Peirani et al. 2008; Teyssier et al. 2009), the Lyman-α forest (e.g., Caucci et al. 2008), as well as propagation of ultra-high energy cosmic rays in the intergalactic medium by combining a semi-analytic method to cosmological simulations (Kotera & Lemoine 2008; Kotera et al. 2009).

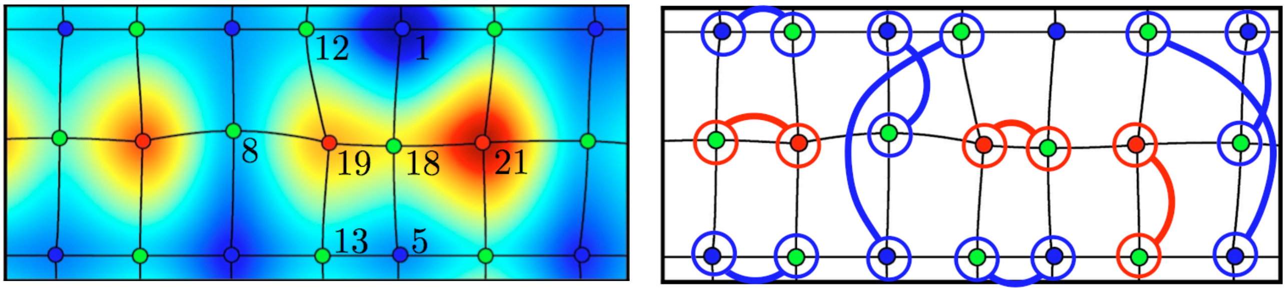


Figure 7.6. *Left: A field and its critical line; right: the pairings in the framework of persistence.*

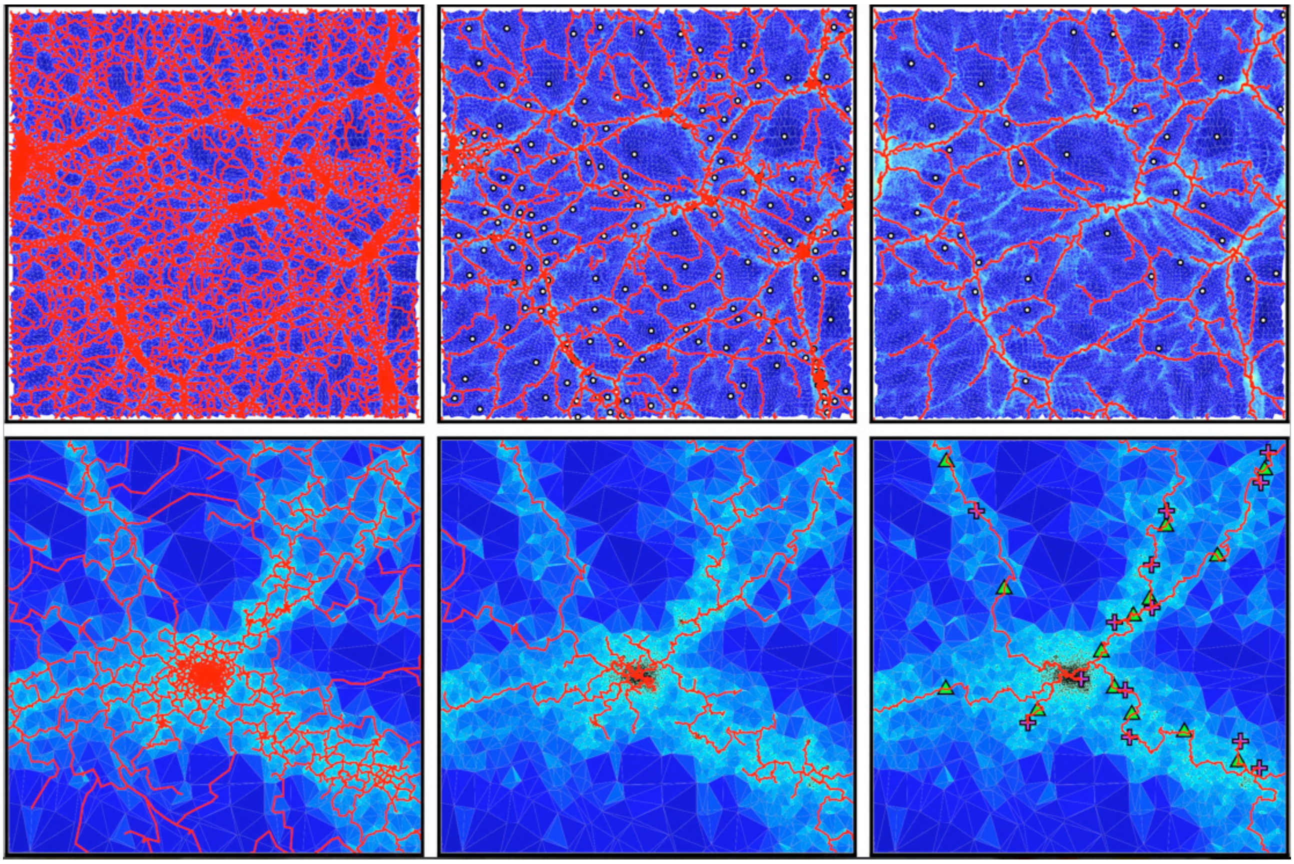


Figure 7.7. *From top to bottom and from left to right, the skeleton at increasing level of persistence, at large scale and in the vicinity of a cluster, in red, superposed to the Delaunay tessellation of a particle distribution extracted from a dark matter simulation (Sousbie, Pichon & Kawahara 2011).*

In the framework of the Planck survey, a special effort is invested in the generation of synthetic CMB maps taking into account the effect of cosmic strings. In collaboration with Louvain University, simulations of cosmic string networks (Ringeval, Sakellariadou & Bouchet 2007) are coupled with photon propagation. For the first time, by generalizing methods developed by Fraisse et al. (2008) and Ringeval (2010), full sky maps have been generated with a resolution of 5' and are currently analyzed for interpreting Planck data.

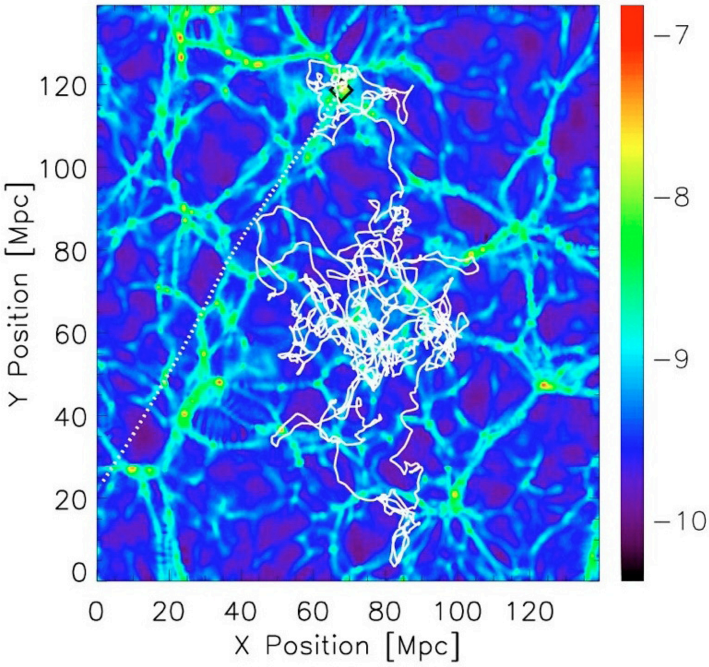


Figure 7.8. *Trajectory of cosmic rays with energy 1018 eV and 1020 eV (straight line) in a intergalactic magnetic field estimated from a cosmological simulation 280 Mpc aside, by supposing that the magnetic field intensity is a function of the underlying matter density.*

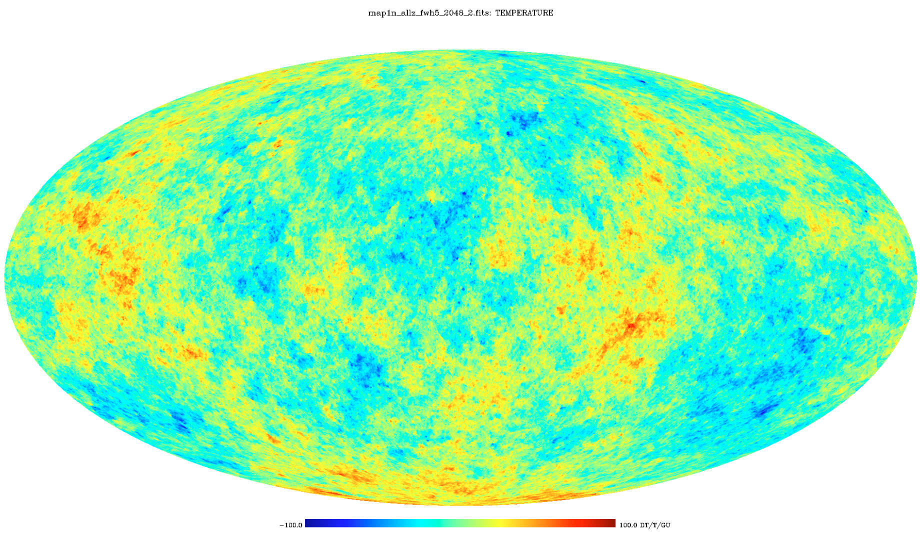


Figure 7.9. *Full sky map of CMB anisotropies induced by ISW effect from Nambu-Goto cosmic strings*

As a complement to numerical simulations, galaxy evolution codes can follow luminosity, color masses and abundances of galaxies according to their type. In that framework, IAP has developed and maintained the code Pégase (http://www2.iap.fr/pegase) as detailed in chapter 3. Coupling such a code to cosmological simulations represents an essential tool to generate realistic mock observations and interpret measurements in large-scale surveys.

Finally, the development of catalog and image simulation tools Stuff and SkyMaker has been pursued (Bertin 2009). New functionalities include redshift evolution of the size of discs and spheroids and variable impulsional response on the field. The two codes have been used in 2010 and 2011 in the framework of preliminary studies to simulate images produced by the adaptive optics wide field imager of project `Imaka (Lai et al. 2008).

IAP also invests a lot of its efforts in developing techniques for the visualization of outputs from numerical simulations. For instance, a code was developed to visualize in real time the particle distribution of an N-body simulation, using video card acceleration with the OpenGL library (T. Sousbie). It can as well display iso-surfaces using the marching cube algorithm, particle tessellations and the skeleton of the distribution. Similarly, the RealGal code (C. Pichon) allows one to create movies of galaxies or distributions of galaxies by relying in a transparent way on public domain software (pov-ray, yorick, mpeg_encode). The ray-tracing code RayT (S. Colombi) allows one to generate pictures from N-body simulations, whatever the size of these latter, by using a sequential procedure for reading data and adaptive smoothing on the fly based on KD-tree decomposition. This software was used for instance to generate a very high-resolution stereoscopic movie from the Horizon-4P simulation.

Figure 7.10. *A 30x30 arcsec stellar field observed (as simulated by SkyMaker) in g, r and i bands from 3.6m CFHT telescope with MEGACAM (right) and what is expected with `Imaka (left).*

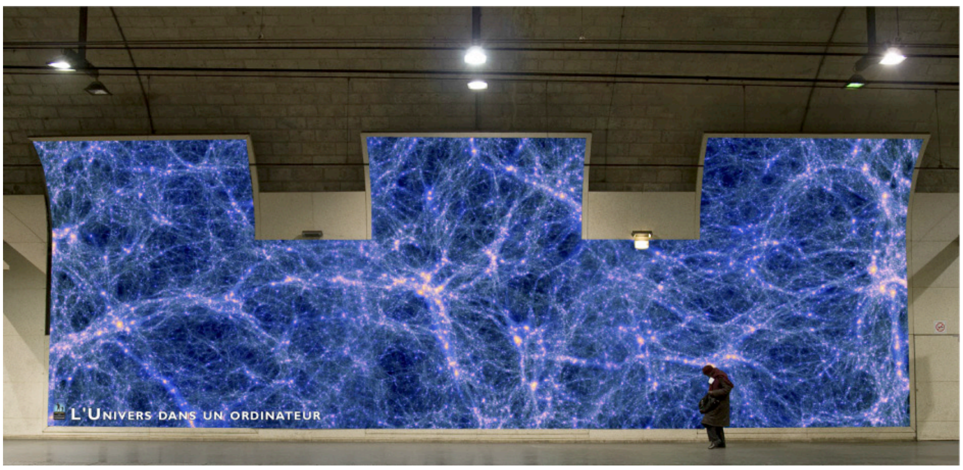


Figure 7.11. *A view of the physical fields in the Mare Nostrum simulation and exposed in 2009 in Luxembourg RER B station in Paris in the framework of the International Year of Astronomy. This picture has 40000x16000 pixels! Courtesy of C. Pichon & J. Mouette.*

Turning to exoplanetary dynamics and ESINPLE project, three codes (particle-in-cell, MHD, kinetic) have been developed to explore the evolution of magnetospheres of extrasolar planets and their interactions with their parent star. This project is the outcome of an international collaboration (IAP, CEA, ESS at Seattle, CBK in Warsaw, LPL in Tucson). A 3D relativistic electromagnetic particle-in-cell code has been developed, which accounts for planetary and stellar magnetic fields, the presence of natural satellites (magnetized or not), and gravity. It offers direct access to microscopic plasma information such as the 3D velocity distribution function, as well as the general 3D topology of magnetic fields and electric currents. A first application has been the study of the terrestrial magnetosphere in the framework of the thesis of S. Baraka (Baraka & Ben-Jaffel 2007, 2011) and serves as a training tool within Forrest project supported by MAE (2011-2013). A second application concerns the magnetosphere of giant solar or extrasolar planets, taking into account stellar and planetary magnetic fields, the presence of a satellite and its intrinsic magnetic field, the rotation of the planet and the inclination of the dipole axis with respect to the spin axis. A project is ongoing on exoplanet HD 189733b to interpret data obtained by the HST in deep UV (Ballester & Ben Jaffel 2011).

In addition, a 3D MHD code describing the interaction of the stellar wind with the interstellar medium is used to simulate the interstellar environment. This code accounts for stellar and interstellar magnetic fields as well as the presence of neutrals (Ratkiewicz et al. 2008) and has been recently supplemented with a solar/stellar wind as a varying limiting condition. This extension requires significant computational resources but allows one to link together in time and space several heliospheric observations obtained at various dates/regions. As a result, deformation of structures such as the heliopause, the terminal shock predicted in details from 2002 (Ratkiewicz & Ben-Jaffel 2002) are repetitively confirmed by in situ measurements of Voyager 1 & 2 as well as energetic atoms of heliospheric origin by Ibex satellite. A large-scale parametric study with the 3D MHD code over a few months allowed us to use the observed distortion to infer a final estimate of the interstellar magnetic field (intensity and orientation) in the vicinity of Solar System (Ratkiewicz, Ben-Jaffel & Grygorczuk 2008; Strumik et al. 2011).

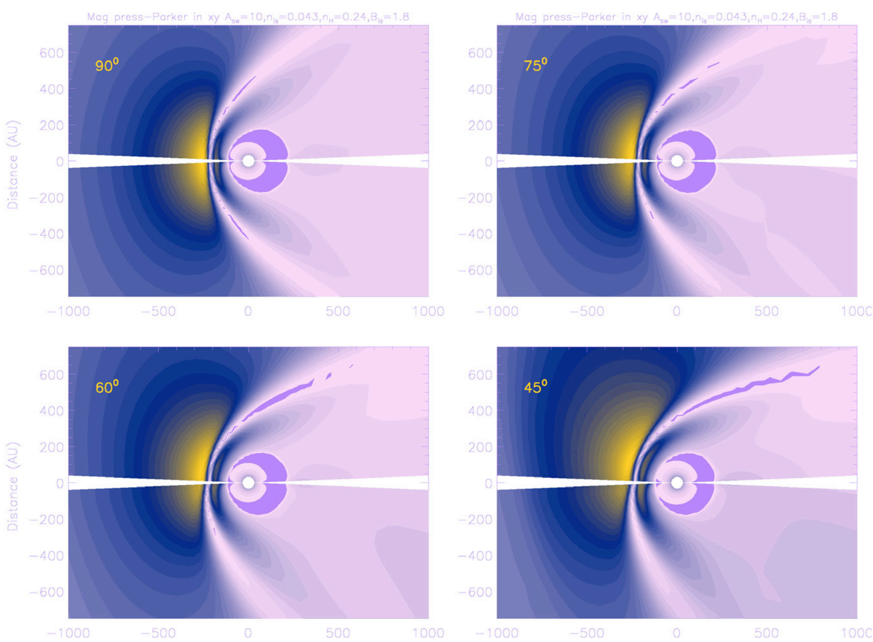


Figure 7.12. *3D MHD simulation of the interaction between stellar wind and local interstellar medium in the presence of interplanetary and interstellar magnetic fields. The figure shows isocontours of the magnetic pressure in a plane orthogonal to the ecliptic containing the solar axis and the direction of arrival of the interstellar wind, for various orientations of the interstellar magnetic field.*

Simulations performed within the framework of ESINPLE project currently use at best a 2563 resolution, but should reach the 5123 level in the near future. Several diagnostic routines have been developed, to study the sensitivity of the code to total number of particles, grid resolution, relative mass of various particles, boundary conditions in terms of gain/loss of particles, reflexivity/periodicity of the fields, etc. This effort allowed us to isolate in the parameter space "recipes" which are the least expensive in CPU and memory. In parallel, a large number of routines (IDL and Fortran) for analysis on the fly of simulation data (Fourier/wavelet analysis, detection of fine structures such as shocks, current sheets, currents aligned with fields lines, etc.) have been developed. Finally, a large effort has been invested to construct IDL visualization tools with the help of J. Grygorczuk (CBK, Poland). The project has now at its disposal various packages (using widgets) optimized to explore various moments of the distribution function, to draw in 3D the magnetic field lines with a point-and-click interface, and to represent the local distribution function of velocities parallel and perpendicular to the field lines. In addition, collaboration with D. Pomarede (CEA) started in 2010 for exploiting and improving SDvision software for 3D data display (particles, isosurfaces, field lines, movies, etc.).

Observations of extrasolar hot Jupiter transits have shown that these planets (which are very close to their host stars) can have an extended atmosphere, which induces significant mass loss (Vidal-Madjar et al. 2003). However, in order to compare these observations to dynamical models of hot Jupiter atmospheres, it is necessary to convert the transit depth measurement in terms of loss rate. IAP has developed a 3D numerical simulation code in order to address this question, taking into account gravitational forces, radiation pressure, radiative transfer inside the evaporating hydrogen cloud in the high atmosphere of the planet and allows one to interpret the transit depth as well as the spectroscopic profile of the absorption, and leads to an estimate of 1010 g/s for the hydrogen escape rate of HD189733b (Lecavelier des Etangs et al. 2010).

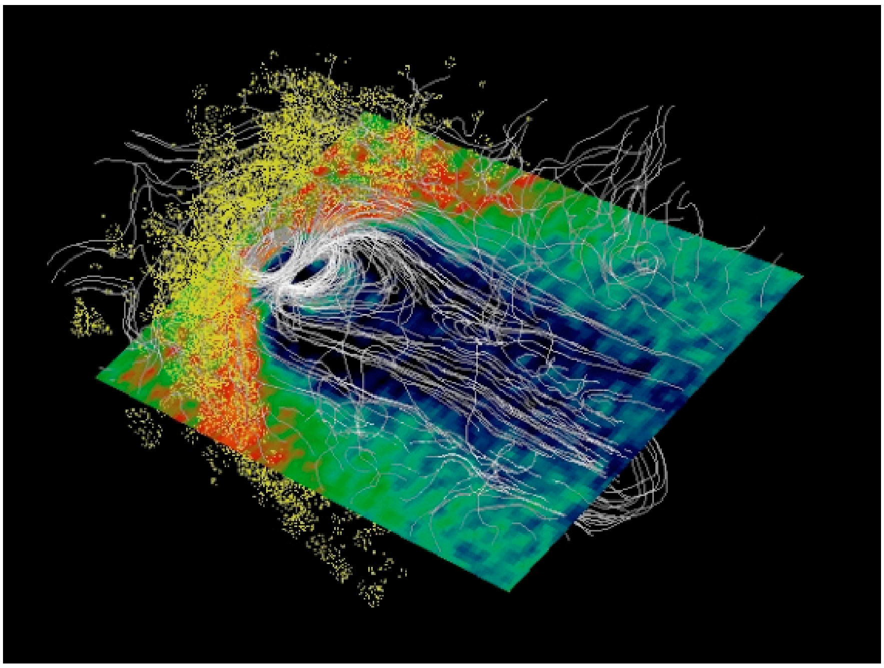


Figure 7.13. *Magnetosphere of an Earth-like planet: Magnetic field lines (white), equatorial plasma density distribution (green), and iso surface of density in the bow-shock and heliosheet region (yellow) are shown in 3D. The stellar wind is impinging from left to right. The density jump appearing as an arch-shape in yellow corresponds to the bow shock position that forms when particles are stopped and reflected by the planetary magnetic field. The fish-like tail is due to the presence of a stellar magnetic field oriented perpendicular to the shown plane. This image was generated with SDvision.*

Turning to high-energy astrophysics, gamma-ray bursts (GRBs) and their afterglows are among the most luminous phenomena in the Universe. They are associated with ultra-relativistic ejecta emitted by a stellar mass compact source. In the most discussed scenario, the burst emission is produced in the jet, from internal energy dissipation through propagation of shockwaves, and the afterglow is associated to the deceleration of the jet by the external medium. In both cases, emission is due to a non-thermal distribution of electrons accelerated in the shocks (see chapter 4). Numerical simulations of GRBs are rendered delicate by the ultra-relativistic nature of the jet dynamics and the great space-time range at play, 10 to 11 orders of magnitude in terms of spatial scale and a radiative timescale much smaller than the dynamical timescale.

In this context, IAP has developed unique simulation tools that can follow all the history of the jet emission, from the moment it becomes transparent until the end of its deceleration. The dynamical code developed since 1998 for internal shocks has been extended to include the effect of an external medium (Genet, Daigne & Mochkovich 2007). It was then coupled to a detailed radiative code (Bosnjak, Daigne & Dubus, 2009), which follows the evolution of electron and photon distributions in the proper frame of the shocks, by including synchrotron radiation, inverse Compton diffusion and $\gamma\gamma$ annihilation. The observed flux is then computed by integrating the comoving emissivity on equal time surfaces of arrival, with relativistic and cosmological effects taken into account. A fine treatment of $\gamma\gamma$ annihilation, essential for interpreting observations at high energies by Fermi, requires a dedicated numerical treatment due to the strong dependence of the process with the interaction angle (Hascoët et al. 2011). Opacity is determined by a triple integral, on the high-energy photon positions and on the direction and wavelength of the low energy photon field, which turns to be strongly anisotropic. All these tools form a state of the art model that places IAP in a very good position to interpret data of satellites Swift and Fermi.

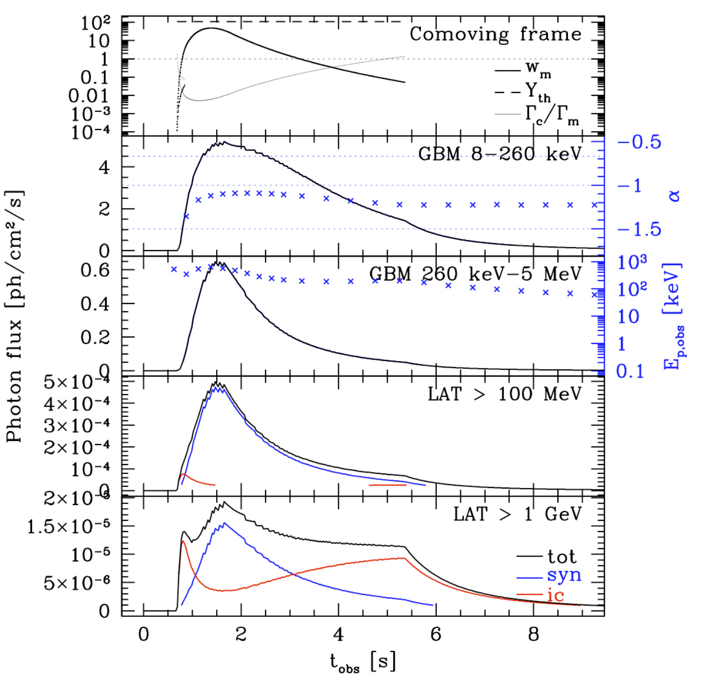


Figure 7.14. *A synthetic GRB obtained from the IAP model. This pulse is produced by an ejecta with a width of 2 light-seconds, made of a "slow" (Lorentz factor Γ=100) and a "fast" part (Γ=400), which leads to an internal collision. This is a building block for more complex lightcurves. Physical conditions in the shocked region: the upper panel shows the evolution of three parameters characterizing respectively the inverse Compton scattering efficiency (YTh), its regime (wm) and the electrons radiative efficiency (Γc/Γm). Observed quantities: the 4 successive panels give the synthetic GRB light curve in different channels of the two instruments (GBM and LAT) of Fermi. Two indicators of the spectral evolution (the peak energy Ep,obs and the low energy slope α) are indicated as well. These results show a good agreement with the behavior observed in the bursts detected by Fermi.*

Finally, it is worth mentioning a program for the visualization of the metric around black holes, which takes into account the full range of relativistic effects produced by these objects (aberration, Doppler shift, intensity, gravitational distortions, image amplification and multiple images). This ray tracing program allows one to visualize what a spectator would see on a circular, elliptic, parabolic or hyperbolic orbit around a black hole, as well as the ephemeral spectacle that one would experience when entering the black hole horizon. From a theoretical point of view, it can also give an impression of how a white hole singularity would seem, or a wormhole, or a naked singularity if such objects were to exist in Nature. The exploitation of this code, developed initially in 2006-2007 by A. Riazuelo, has lead to numerous contributions to the general public, to an Astronomical Picture of the Day, and especially to the production of a 38 minutes DVD (Desenne, Riazuelo & Rouat) of which nearly 25000 copies were sold.

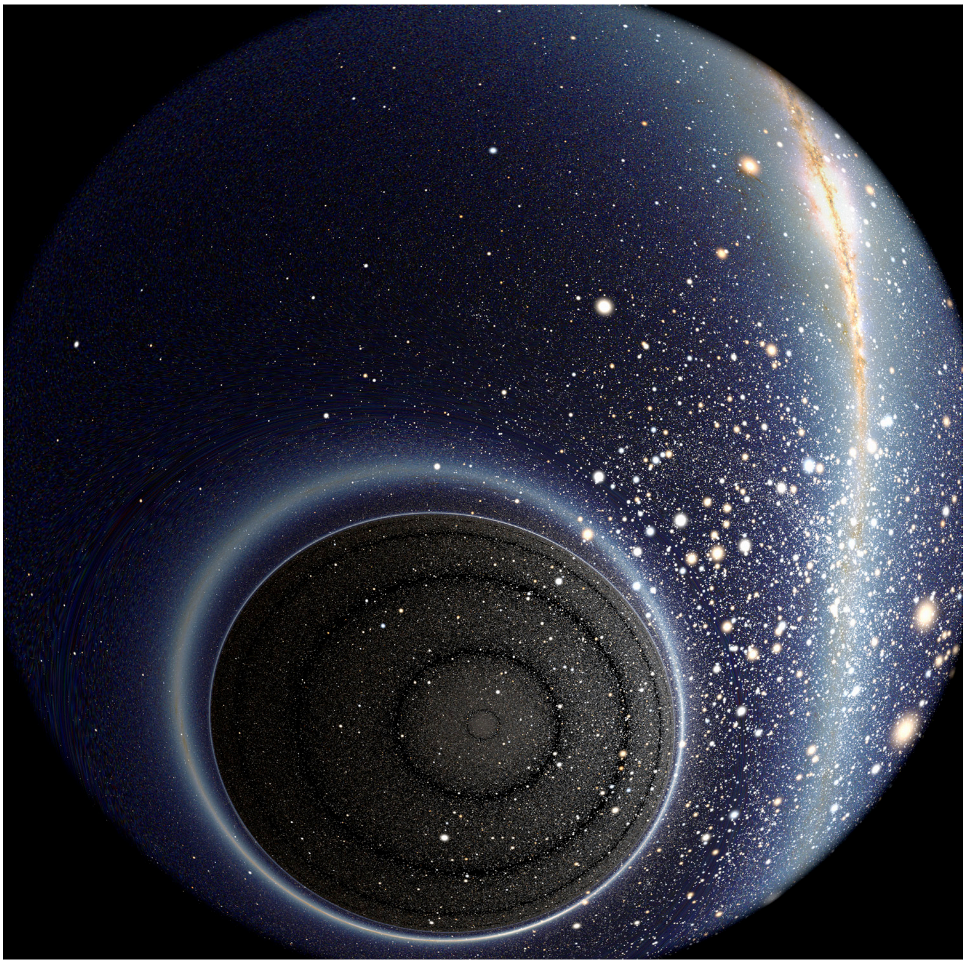


Figure 7.15. *Orbiting around a nearby wormhole.*

This DVD was also distinguished by two prices. In 2009, a version for numerical planetariums has been realized (with a fish-eye resolution of 4000x4000) in the framework of collaboration with RSA Cosmos and is now shown in various planetariums around the world. Thanks to a sponsoring program "Passion for Innovation" of Dassault Systèmes, it just became possible to improve the software so that it can be used in real time (50 frames/sec) and in high resolution (1920x1200).

7.2.5 Herschel

The European submillimeter space observatory Herschel was launched with Planck in May 2009, and will operate until early 2013. It offers many pointed observing modes between 60 and 600 μm, addressing a very wide range of scientific topics, such as Solar system physics, star formation, stellar evolution, interstellar medium physics and chemistry, galaxy evolution, and cosmology. Major progress with respect to previous infrared space telescopes is brought by a combination of technical characteristics: wide spectral coverage, allowing simultaneous measurements of the peak and Rayleigh-Jeans part of the thermal emission of dust; improved resolving power; high sensitivity, mainly limited by the source confusion noise; advanced spectroscopic capabilities; and high mapping efficiency.

Five staff researchers and two postdoctoral fellows of the institute directly participate in the scientific exploitation of Herschel. Two of them also contribute technical work to the ICC (Instrument Control Center, an organism responsible in particular for the data processing pipeline and all calibration activities) of the SPIRE instrument, supported part-time by a computer engineer. Within the SPIRE ICC, they are members of the Scan Map Pipeline Validation Team and the analog for the Fourier Transform Spectrometer.

Software for Scan Observations, and Extended Source Flux Calibration

We have developed and made public a software to process scan data, whose main task is the subtraction of brightness drifts caused by thermal fluctuations of the cryogenic bath and the flicker noise of the bolometers (Scanamorphos; Roussel 2011, http://www2.iap.fr/users/roussel/herschel). This tool is based on different principles from those of the official pipeline, since we do not use any noise model, unavoidably incomplete, but instead extract the drifts from the data themselves, by exploiting the redundancy built in the scan observations. Scanamorphos is currently the only public map-maker that preserves both compact sources and extended emission for the PACS instrument (for which the drift subtraction is the most difficult), while removing a major part of the noise. It will continue to be maintained through the entire mission.

The flux calibration performed by the SPIRE ICC is strictly valid for point sources, because it does not take into account the beam size variations within each of the three bolometer arrays. Using Scanamorphos, we have calibrated the relative beam sizes from scientific observations of bright Galactic regions, thus keeping the volume of calibration observations unchanged. We obtain beam size variations of the order of 10%, with a coherent spatial pattern, that have been successfully tested and are being included in the pipeline.

Morphological Analysis of Interstellar Clouds

We have adapted a software, initially developed for cosmological simulations (DisPerSE; Sousbie 2010, Sousbie et al. 2010), to extract filamentary structures from interstellar cloud maps, and quantify their topological properties and their density and temperature distributions. This tool is essential to test and refine models of molecular gas formation and accretion, as well as models of star formation.

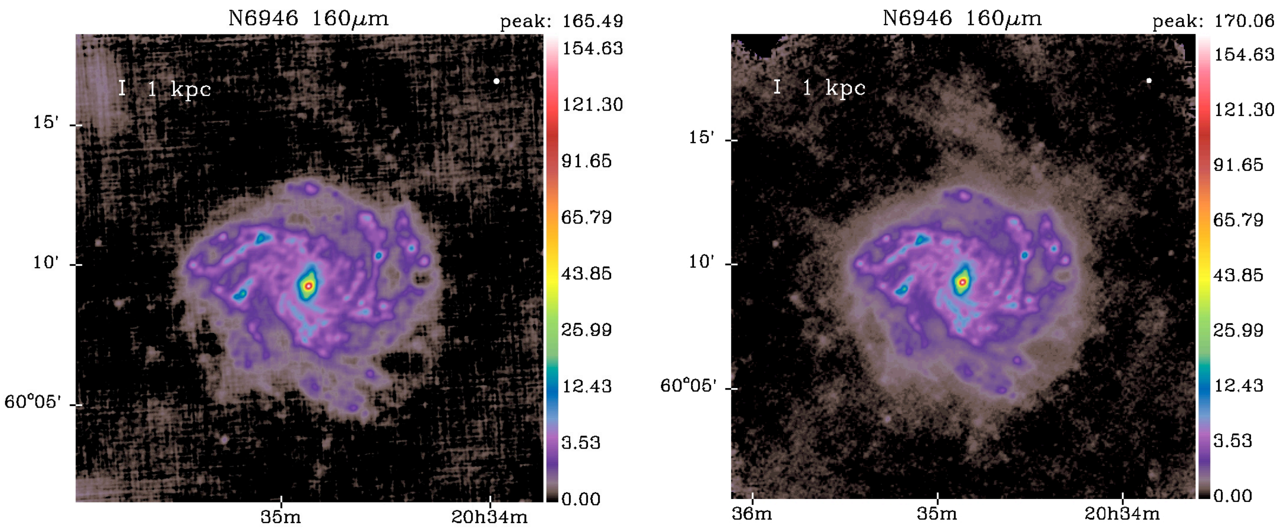


Figure 7.16. *Left: map of the galaxy NGC 6946 at 160 microns, processed with the official pipeline. Right: same data processed with Scanamorphos. Maps produced by the pipeline are much noisier, and lack a substantial fraction of the diffuse emission of the galaxy and foreground cirrus emission.*

7.2.6 BOSS

BOSS is one of the four surveys of SDSS-III (Sloan digital sky survey III). This project, dedicated to the search of Baryonic Acoustic Oscillations, involves members of APC (IN2P3/CNRS), of IAP, LAM and Observatoire de Besançon (INSU/CNRS) and of CEA (IRFU).

Evidence has accumulated over the last years that the expansion of the Universe is accelerating. Within the framework of the standard cosmological model, this implies that 70 % of the universe is composed of something that has been called dark energy, and which counters the attractive force of gravity. Dark energy could be Einstein's cosmological constant, or some exotic field called quintessence, or more generally could mean that the laws of General Relativity are incomplete. Elucidating its nature is one of the major topics in cosmology today, and could have implications for astronomy, particle physics, general relativity, and string theory.

One of the techniques allowing to measure precisely the cosmic expansion history over a wide span of time is the "baryon acoustic oscillations" (BAO) method, pioneered in the SDSS-I project. Sound waves that propagate in the hot plasma of the early Universe imprint a characteristic scale on the clustering of dark matter, galaxies and interstellar gas. By measuring this scale with tracers seen at different distances, one can determine how the Universe has grown and how that growth has been affected by dark energy. More specifically, the main goal of BOSS is to measure, through the BAO method, the equation of state (EOS) of dark energy and its evolution with redshift.

We propose to map the 3-D distribution of 1.5 million luminous red galaxies and the neutral hydrogen gas absorption in the spectra of 160 000 distant quasars. The galaxy clustering measurement will determine the absolute distance scale with 1% precision over the last 7 Gyr. Clustering in the quasar absorption spectra will allow 1.4 % measurements of the distance scale and the cosmic expansion rate at a lookback time of 10 Gyr, providing a precise determination of the curvature of space and unique sensitivity to dark energy at early times. The survey SDSS-III has started in 2008. Since then, our group and the French Participation Group to SDSS-III are focused on the part of the survey aimed at recovering the BAO signal from quasar measurements. We lead the target selection and the preparation of the data catalog.

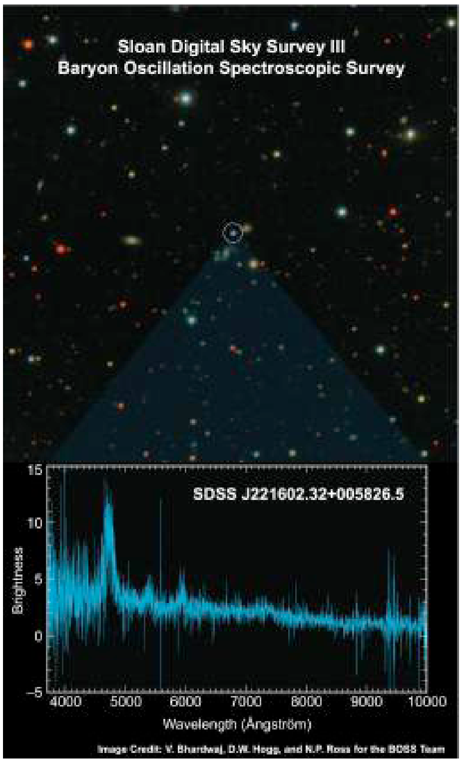


Figure 7.17. *One of the "first light" spectra taken by BOSS. The top panel shows the targeted blue quasar, highlighted in the image of the sky. At the bottom is shown the BOSS spectrum of the object. BOSS plans to collect millions of such spectra and use their distances to map the geometry of the Universe. Figure credit: D. Hogg, V. Bhardwaj and N. Ross.*

The IAP members working on BOSS are P. Petitjean, P. Noterdaeme, E. Rollinde, S. Peirani, I. Pâris et H. Finley. I. Pâris has obtained her PhD degree in December 2011, while H. Finley started her PhD in September 2011. We were granted an ANR to join the SDSS collaboration, and to hire two post-docs, among which Sébastien Peirani who is now permanent at IAP. Thanks to the additional support from PNCG and CSA, we regularly participate at SDSS collaboration meetings and we have organized a workshop at IAP in July 2012.

Our general contribution in BOSS, and more specifically in the target selection procedures and in the data post-processing have been recognized by the SDSS collaboration as four members of the French Group (E. Aubourg, P. Petitjean, I. Pâris, C. Yèche) have been selected as architects of SDSS-III. The status of architect allows them to co-sign any paper that makes use of SDSS-III data before the public release. Due to her implication in the preparation of the quasar catalog, I. Pâris should be in charge of the next data release paper.

Besides the BAO signal itself, we will shortly use the wealth of data from BOSS to publish new results on DLA statistics, continuum propertyes, and quasar-absorbant correlation.

7.2.7 The Consortium Exoplanets SOPHIE

Simultaneously, with the installation of the SOPHIE spectrograph to the 193-cm telescope at the Observatoire de Haute-Provence, a consortium of observers was set up in order to carry out a competitive and coherent program of search and study of the exoplanets using this instrument. This Consortium Exoplanets SOPHIE aims at bringing constraints on the planetary formation processes and at physically characterizing these systems.

The Consortium Exoplanets SOPHIE combines about twenty researchers from six institutes (IAP, OHP, LAM, IPAG, Geneva, Porto). It is organized around five subprograms, each one aiming at a particular planet population and stars hosts, and a given observational mode of SOPHIE:

- subprogram 1: high precision for the research of the super-Earths;
- subprogram 2: moderate precision for the research and the study of giant planets;
- subprogram 3: planets around M dwarfs;
- subprogram 4: planets around early-type stars;
- subprogram 5: long-period planets search, using the database available since 1994 at OHP.

The collaboration of these five subprograms optimizes the time scheduling at the telescope and allows expertise and competences of the members of the consortium to be shared. As a whole, this program has 130 to 180 nights a year with SOPHIE.

The consortium includes several IAP members: F. Bouchy (PI), G. Hébrard (responsible of a sub-programs), A. Vidal-Madjar (member of the consortium until 2010), Rodrigo Diaz (postdoc from 2009 to 2011), Isabelle Boisse (thesis defended in 2010). A. Lecavelier also collaborates in some studies. The database of the observations is located at IAP. This project is supported by ANR and PNP (INSU).

More than fifteen refereed papers have been published by the Consortium up to now. IAP members are deeply involved in all these publications, and are first authors of the majority of them. Among the results already obtained, one can quote the detection of new planets (e.g. Bouchy et al. 2009, Hébrard et al. 2010, Boisse et al. 2010, Diaz et al. 2011, Boisse et al. 2012), the study of the stellar activity of planet-host star HD189733 (Boisse et al. 2009), or the detection of the light transmitted by the terrestrial atmosphere by the observation of a Moon eclipse, simulating the observation of an hypothetical future exo-Earth in transit (Vidal-Madjar et al. 2010). One of the results with the strongest impact is the discovery of the first two cases of misaligned extrasolar systems (Hébrard et al. 2008, Moutou et al. 2009, Hébrard et al. 2010). These systems with non-null obliquities jeopardize standard models explaining giant planet formation from migration in the cirucumstellar disks.

Scheduled to extend over 10 years, the Consortium Exoplanets SOPHIE will stand at least until 2016. It will benefit from the significant improvements made in 2011 on SOPHIE, which now allows low-mass planets to be reached. At longer term, the gained experience will be reinvested in the exploitation of SPIRou, an infrared spectropolarimeter scheduled for 2015 at CFHT.

7.3 Projects (II)

7.3.1 Inspire

Inspire is a UV interferometer-polarimeter project that will embark on a suborbital rocket. It is supported by NASA and CNES and will better define the structure of the interplanetary medium as well as measure the magnetic field at the surface of Jupiter. The French team is responsible for delivering a calibrated holographic grating provided by the Jobin-Yvon company and building a radiation transfer code for the interpretation of future spectro-polarimetry data. The US team is responsible for building and flying the Inspire payload. F. Vincent, a PhD student from UPMC, obtained a scholarship (2007-2011) from UC Davis and just defended his thesis on the project.

The first grating provided by Jobin-Yvon in 2007 showed an anomaly in its efficiency that depends on the incidence angle of light. The team had to characterize the anomaly, analyze its origin, and correct it. This process lasted 3 years, a delay that directly affected the rocket's launch.

The team published 9 refereed papers and many communications. The team's production branched off into 4 directions:

- The Hanle effect, proposed for the first time in planetary sciences, measured the surface magnetic field of Jupiter (Ben-Jaffel et al., 2005, 2007)
- The detection, analysis, and correction of an anomaly in the efficiency function of a holographic grating in the far UV regime. The efficiency-angle curve provided will be very useful in many interferometry UV applications (Vincent et al., 2011).
- An electromagnetic and relativistic PIC 3D code was proposed to study (exo) planetary magnetospheres (Baraka and Ben-Jaffel, 2007, 2011).
- MHD 3D simulation of the solar wind-LISM interaction helped fully uncover the ISM magnetic field strength and orientation in the vicinity of the solar system (Ratkiewicz, Ben-Jaffel, and Grygorczuk, 2008; Strumik, Ben-Jaffel, et al., 2011). This discovery simplifies studying the interplanetary medium by revealing one of the key parameters that produces the heliosphere's distortion.

The French team fulfilled its duty with the gratings provided and software developed. Nevertheless, because of the uncertainty about NASA's launch facility, we decided to temporarily stop our participation in the project in hopes that the US team will be in a position to prepare and launch the Inspire payload. This position, validated by CNES, allows the US team to use the French gratings while leaving the door open for future participation in the data analysis of the next rocket flight (expected in 2012).

Finally, a micro-satellite project is under study to map the sky at Lyman-a (121.6 nm) at high resolution. The idea is based on using the Spatial Heterodyne Spectrometer (SHS) developed for Inspire to accurately measure the heliospheric distortion produced by both the interstellar magnetic field and the solar wind (Vincent et al., 2001b). The project will be proposed to CNES in 2013.

7.3.2 PLANET, HOLMES: Gravitational Microlensing Search for Extrasolar Planets

Amongst the various techniques to search for extrasolar planets (radial velocities, transits, direct imaging, astrometry, pulsar timing), microlensing is particularly well-suited to detect low-mass planets at large orbital distances from their host stars, and for a wide range of masses (from super-Earths to giant planets). These planets are located between 0.5 to 10 Sun-Earth distances, and for most of them orbit low-mass M-dwarf stars. They are thus living beyond the ice-line, which is the region where ice can exist, and thus where planets are supposed to form. Low-mass planets at such large distances from their stars can only be detected by the microlensing method.

The group at IAP is coordinating the international PLANET collaboration (Probing Lensing Anomaly NETwork) since 2002. It comprises around 35 scientists from about 10 countries. It relies on a network of telescopes located in the Southern Hemisphere, which evolved from a 4-telescopes network to almost 40 telescopes, with a significant fraction of amateur telescopes (working on alerts). Ongoing microlensing events are being followed-up and modeled in real-time, with light curves available online (http://planet.iap.fr).

Amongst the most important results are the detection of the first super-Earth by any technique, OGLE 2005-BLG-390Lb (Beaulieu et al. 2006, Nature), and a global statistical result on planet frequency for cool planets with orbits 0.5-10 AU (Cassan et al. 2012, Nature), both led by IAP astronomers. Many other results were obtained in 2007-2011, such as the discovery of very massive Jupiter-like planets around low-mass stars (Dong et al. 2009, Batista et al. 2011), which pose challenges to planet formation scenarios, cold Saturns and Neptunes (Janczak et al. 2010, Sumi et al. 2010, Miyake et al. 2011, Muraki et al. 2011), a 1/2 scaled analog of the Solar System (Gaudi et al. 2008), and a planet of 3 times the mass of the Earth (Kubas et al. 2010).

Wide-Field Telescopes, EUCLID-MLENS, WFIRST (2012-2020)

The next step for microlensing is to detect other super-Earths and Earth analogs, while extending the statistics to the low-mass tail of the planetary mass function. New networks of wide-field imagers mounted on robotic telescopes (2012-2020) will increase dramatically the number of microlensing events monitored and the planet discovery rate. The group at IAP will actively collaborate with two telescopes in Australia and Tasmania, with interactions with OGLE in Chile, WISE in Israel, MOA in New Zealand, and possibly collaborating for deploying a new telescope in Namibia or South Africa.

Microlensing from space would allow detecting planets as small as Mars, and provide strong constraints of the planetary mass function in its fine details down to Earth-like planets. A 10-months program onboard EUCLID (ESA) would fulfill the requirements to achieve such goals. The group at IAP is in charge of the microlensing onboard EUCLID, and is also closely in relation with the US project WFIRST.

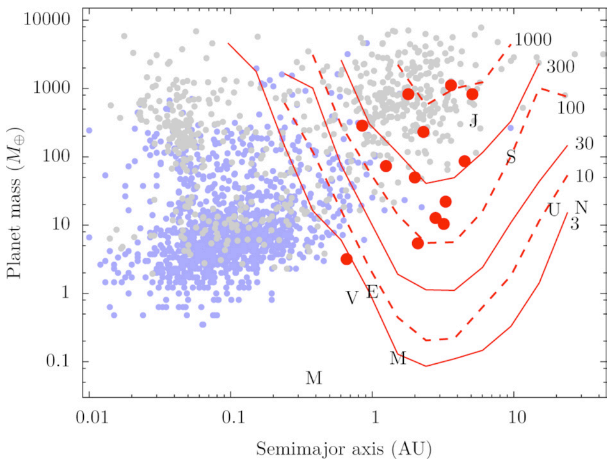


Figure 7.18. The gray dots mark the planets detected up to now, while blue points are planet candidates from the Kepler spacecraft. Red dots mark planets detected by microlensing, and red contours indicate the expected number of detections with a 10 months survey using EUCLID, if all stars had one planet.

7.3.3 ECHO

ECHO (Exoplanet Characterisation Observatory) is one of the four projects preselected by ESA for its M3 space mission in the framework of COSMIC VISION 2015-2025 (launch date 2022). It will be the first mission to be entirely dedicated to the study the physics and chemistry of exoplanet atmospheres. It is designed to answer the questions of the conditions of the emergence of life, with comparison to conditions existing on Earth. These questions are: What are the conditions of planet formation and emergence of life? Are solar-like systems rare or common?

During the primary transit, a fraction of the star light is absorbed by the limb of the atmosphere of the planet, thus leading to a measurement of the transmission spectrum of the planet's atmosphere. During the secondary transit, it is possible to acquire an emission spectrum in the infrared of the atmosphere by comparing the spectra just before and just after the planet passes behind the star, as well measuring in the visible the star's reflected light. Using the modulations between different orbital cycles, thermic gradients in the atmosphere can even be constrained.

ECHO is designed as a 1.2 to 1.5 m space telescope, with spectrographs that will probe exoplanet atmospheres in the wavelength ranges 0.5-16 microns, with a typical resolution of 1000 to 20. The technology needed for ECHO is simple and already well known, with passive cooling systems providing a great stability for the instruments. This project includes around a hundred scientist from many countries (Tessenyi et al. 2011, Tinetti et al. 2011), with an important contribution from France. J-P. Beaulieu (IAP) is the French coordinator, and the ECHO web page is based at IAP.

7.3.4 EROS

A number of microlensing dark-matter surveys have produced tens of millions of light curves of individual background stars. These data provide an unprecedented opportunity for systematic studies of whole classes of variable stars and their host galaxies. One interesting result was to use the EROS-2 survey of the Magellanic Clouds to detect and study the population of beat Cepheids (BCs) in both Clouds. BCs pulsating simultaneously in the first overtone and fundamental modes (FO/F) or in the second and first overtone modes (SO/FO) are of particular interest. Using special software designed to search for periodic variables, we have scanned the EROS-2 data base for variables in the typical period range of Cepheids. Metallicities of FO/F objects were then calculated from linear non-adiabatic convective stellar models. We identify 74 FO/F BCs in the LMC and 41 in the SMC, and 173 and 129 SO/FO pulsators in the LMC and SMC, respectively; 185 of these stars are new discoveries. For nearly all the FO/F objects we

determine minimum, mean, and maximum values of the metallicity. The EROS data have expanded the samples of known BCs in the LMC by 31%, in the SMC by 110%. The FO/F objects provide independent measures of metallicities in these galaxies. The mean value of metallicity is 0.0045 in the LMC and 0.0018 in the SMC. The figure 7.19 below shows our FO/F BCs in Magellanic Clouds, compared to known ones in the Galaxy and M33, on a composite Petersen diagram in which the isometallicity lines delimit the lower and upper boundaries, respectively, of the range in which both Fand FO modes are linearly unstable; this is the linear criterion for beat-pulsations. This is a new and elegant method to measure the metallicity distribution in galaxies.

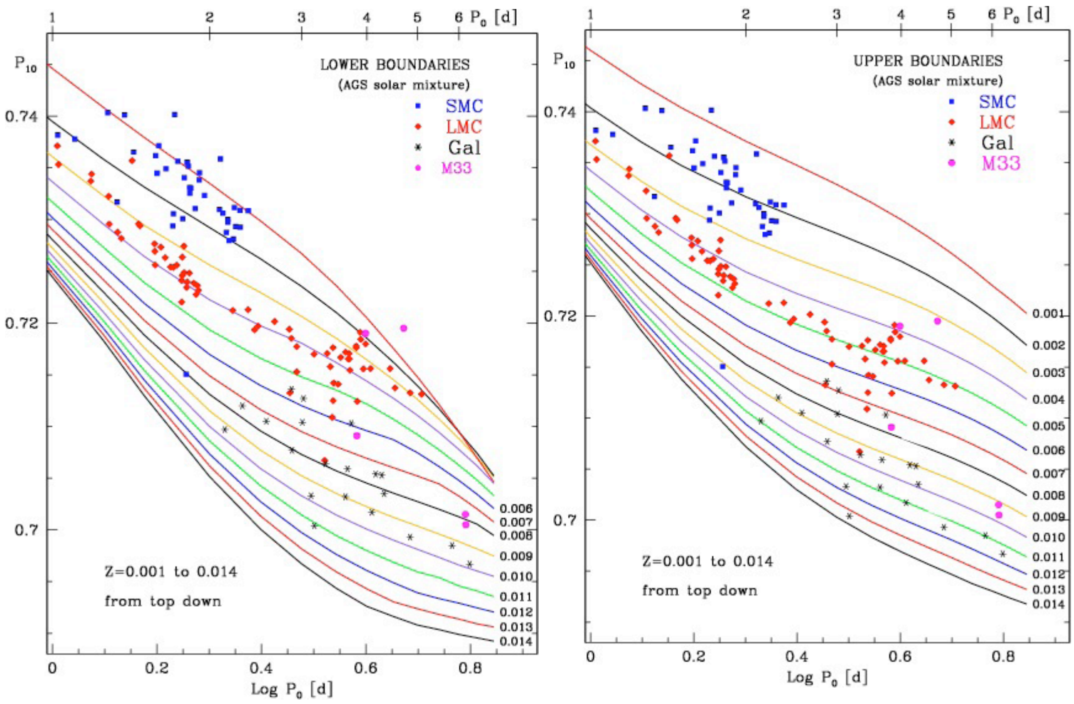


__Figure 7.19.__ Composite Petersen diagrams (P10 = P1/P0 vs. P0) of the FO/F BCs from EROS-2 compared to other known stars. The lines delimit the periods for which both F and FO are linearly unstable at given Z (lower and upper boundaries in Z for given P10 and P0). The metallicity increases downward from Z = 0.001 (top line) to 0.014 in steps of 0.001.

Outlook. For public use, 87 millions of light curves from the EROS-2 experiment were transferred to the Time Series Center (TSC) of the University of Harvard (Cambridge, Massachusetts). All data from EROS-2, MACHO and OGLE 2 can be found at http://timemachine.iic.harvard.edu/search/ which thus enables us to compare data for given targets which come from different observing campaigns. The catalogs of all 87 millions of light curves will be published by CDS to which will be added some 13284 reference images in two color EROS-2 bands. The EROS-2 images will also be stored in ESO's Science Archive. The images need however to be translated into ESO standards which represent a huge work investment. A collaboration with the Geneva Observatory will be pursued to established classification of variable stars observed with GAIA.

7.3.5 SVOM

The Space-based multi-band astronomical Variable Objects Monitor (SVOM) is a Chinese-French mission (http://smsc.cnes.fr/SVOM/) devoted to the detection and observation of gamma-ray bursts (GRBs) and their afterglows (see chapter 4.1.2) to understand these phenomena and use them as astrophysical tools, especially for cosmology. The project consists mainly of a satellite (see 7.20) with a large field gamma-ray telescope for the detection of GRBs, a gamma-ray detector to extend the spectral coverage to the MeV range, and several telescopes for the detection and follow-up of the early afterglow in X-rays and optical. Ground-based instruments complement the satellite: wide field cameras (GWAC) for the detection of the prompt optical emission, and two robotic telescopes (GFTs) for the optical follow-up of the afterglow. One GFT, provided by France, has near-infrared capabilities (J band), which is well adapted for the most distant GRBs.

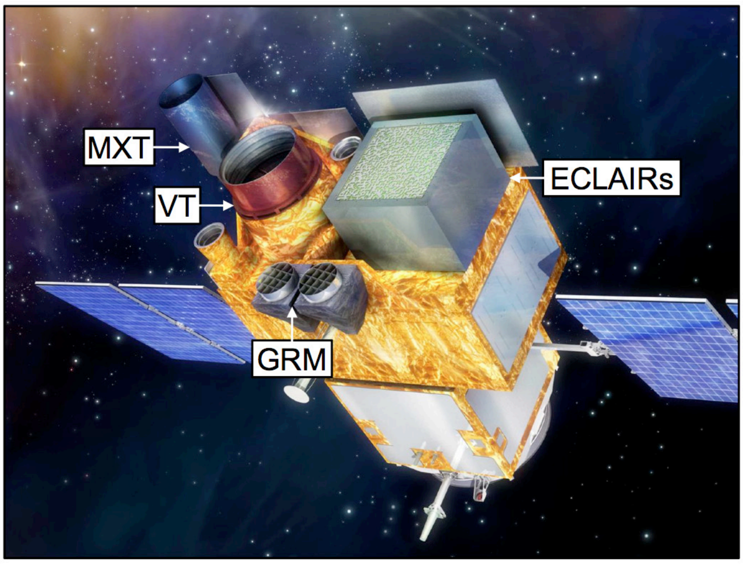


***Figure 7.20.** The SVOM satellite: SVOM will operate several instruments in space: (1) ECLAIRs, a telescope for the detection and localization of GRBs. Spectral range: 1 to 300 keV; (2) GRM, a monitor of the prompt gamma-ray emission 50 keV and 5 MeV (4 detectors); (3) MXT, a X-ray telescope for the detection of the X-ray afterglow. Spectral range: 0.3 to 7 keV; (4) VT, a visible telescope for the follow-up of the early afterglow in the visible. MXT and VT are narrow field instruments compared to ECLAIRs: an automatic slew of the satellite is necessary, based on the near real time localization computed on board from the ECLAIRs data. Ground-based instruments complement the scientific payload of the satellite: (1) GWAC, a wide field instrument to detect the prompt optical emission; (2) the GFTs, two robotic telescopes (diameter: 1 m) to follow the afterglow in the visible, and for one GFT, in the near infrared (J band).*

The main objectives of SVOM are: (1) to detect during the nominal duration of the mission at least 200 GRBs of all types (long and short, X-ray rich, etc.); (2) to observe the prompt emission in the 1 keV-5 MeV range in order to well characterize the burst spectrum and its evolution; (3) to observe simultaneously (including the search for precursors in the 5 minutes before the gamma-ray trigger) the prompt visible emission in more than 25 % of the GRBs (limit V magnitude: 15); (4) to measure in less than 10 seconds the position of the burst with a 10 arcmin accuracy (1 arcmin accuracy for 50% of the bursts) and to transmit this position to the ground in real time so that it is available for the community in less than 1 minute; (5) to start the visible and near-infrared follow-up of the afterglow in less that 5 minutes after the GRB. After the small robotic telescopes have detected and observed the early afterglow, the position of the burst is known with a 1 arcsec accuracy, which allows following the source on longer timescales with large telescopes. In particular, France is contributing to XSHOOTER, a second-generation instrument at VLT since the end of 2008. The rapid-response mode of VLT allows pointing an afterglow within 15-30 minutes after an alert. XSHOOTER has been especially built for rapid spectroscopy, in order to measure the afterglow spectrum when the source is still very bright. This instrumental strategy from space to robotic and large telescopes on ground opens the possibility of using GRBs as tools for cosmology, especially from the spectroscopic analysis of the absorbers located in front of the GRB on the line-of-sight (see chapter 4, §4.5). GRBs can extend the present interval of redshifts to hopefully reach the epoch of reionization and of formation of the first stars.

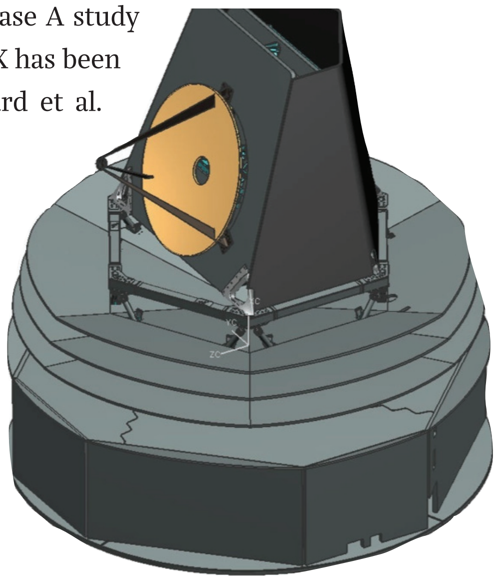
In France, the SVOM project is under the responsibility of CNES. Several institutes are involved: the Astrophysical Division of CEA (CEA/Irfu/SAp), the Research Institute in Astrophysics and Planetology (IRAP) in Toulouse, the Observatoire de Haute Provcence, the Laboratory for Astrophysics in Marseille (LAM), the Astroparticle and Cosmology (APC) laboratory in Paris, and IAP. The French PI and co-PI are Jacques Paul (CEA/IRFU/SAp) and Stéphane Basa (LAM). A Memorandum of Understanding (MoU) between France and China has been signed in October 2006 by CNES and the Chinese Space Agency. Recently (autumn 2011), the responsibility of the project on the Chinese side has been transferred to the Chinese Academy of Sciences. Phase A of SVOM finished in January 2009 and phase B should have already started. The delay is mainly due to the difficulty for China and France to find an agreement on the choice and the cost of the platform satellite. This has slowed down the project until autumn 2011. However, the development of the space and ground-based instruments never stopped. Regarding the scientific payload on SVOM, France is providing the ECLAIRs telescope, and the MXT telescope in collaboration with Leicester University. The launch date of SVOM will not be earlier than 2015, and will be fixed once the phase B has started and the project has resumed its normal development (hopefully first half of 2012).

IAP has three co-investigators of SVOM, within the research group COSMOH: F. Daigne, R. Mochkovitch and P. Petitjean. F. Daigne is one of the four mission scientists whose role is to assist the PI in all decisions impacting the scientific program. Two computer engineers (L. Domisse and G. Missonnier) also participate in the project. The first contribution of IAP is to the scientific support to the mission, which has been briefly presented in chapter 4, §4.1.2, and is mainly related to building a GRB population synthesis model to estimate the detection rate by SVOM and to optimize the trigger algorithms and the strategy for the follow-up. This work is done in close collaboration with the teams at CEA/IRFU/SAp and IRAP that build the ECLAIRs instrument and Scientific Data Processing Unit on board. IAP is also contributing to the development of the French Science Center (FSC), led by CEA/IRFU, the role of which is to receive data, generate and distribute alerts, produce and archive the scientific products. IAP has mainly contributed to the definition of the alert strategy, and of the high-level scientific products of the core program (GRBs), especially the products that are generated from data obtained with several SVOM instruments (space or ground). In the next phase, we will contribute to the definition of the corresponding algorithms and the coding of the associated modules in the data processing system, as well as the preparation of the open window of SVOM, i.e. the interface offered to the scientific community to access some of SVOM GRB data.

7.3.6 The Molecular Hydrogen Explorer Project: H2EX

The Molecular Hydrogen Explorer (H2EX) was proposed in response to the ESA 2015 – 2025 Cosmic Vision Call as a medium class mission. The leading roles for the study and the design of the payload was played by IAS (Orsay – France) and IAP, in an international consortium of 30 institutes. The mission was conceived in order to help understand the formation of galaxies, stars and planets from H2, the basic material, through surveys of the warm molecular gas (($\geq$ 100 K) in a large variety of site. The instrument was based on an innovative wide-field (20' in diameter) imaging Fourier Transform Spectrometer, able of a resolving power of up to 30,000 at 10 μm, to observe the S(0) to S(3) lines of H2 (28.2 to 9.7 μm). The payload with a 1.2 m telescope was designed to reuse the PLANCK platform and the passive cooling design.

Finally, the mission was not selected for a Phase A study but the science program remains topical. H2EX has been presented in a paper from Boulanger, Maillard et al. 2009 [Exp. Ast., 23, 277].



Mid-Term Plan

(2014 – 2018)

8

IAP as a Research Institute

IAP has experienced a rapid evolution during the last 12 years. Its status has changed in 2000 from a pure CNRS laboratory to a joint CNRS – Université Pierre et Marie Curie unit and an "Observatoire des Sciences de l'Univers" of the UPMC. The GreCo, a group of theoretical Physics has been incorporated in the Institute in 2005, and new scientific teams have been created between 2005 and 2008. In parallel, the scientific domains tackled by IAP staff have also evolved with growth in the fields of exoplanets, extragalactic Astrophysics, Cosmology and theoretical Physics. The same period has seen the end of instrument development and the emergence of two large data centers: TERAPIX for wide field imaging first, and the Planck Data Processing Center. While the IAP is now widely recognized as a center of excellence in observational and theoretical cosmology, it has maintained very diverse domains of interest, covering almost all of Astrophysics. For example, IAP has pioneered or has had a leading role in the development of several domains in modern Astrophysics, such as the search of exoplanets by microlensing, exoplanet atmosphere analysis during transits, wide-field imaging, strong and weak gravitational lensing measurements, very high resolution absorption spectra of distant QSOs, numerical simulation of the large scale structure formation, or mm observations of very distant QSOs and starburst galaxies.

With a project targeted to observational and theoretical Astrophysics, the scientific domain of IAP is fundamental research, without direct application for the general public. However, as an actor of pure science, IAP has also a mandate to share the advance of science with the general public and with children in schools, to develop awareness of the scientific culture. Moreover, IAP has teaching duties at a higher level, at the Universities or engineering schools. And finally, as an "Observatoire des Sciences de l'Univers (OSU)", IAP has responsibilities in making observations of the sky available to the largest possible community. These are the four pillars of the IAP project: Research, observational data processing and dissemination, teaching, and outreach. They are all important and complementary. And they all require attention and support by the direction of the Institute and the staff.

Research Project

In line with a strategic plan defined in the early 2000s, a set of priorities for IAP has been defined in 2007 along 6 lines, as described in the Introduction.

These objectives have been used in the last 5 years with some success. They are still valid. And they can continue to be our guidelines for the next 5 years. However several factors have contributed to strengthen the research in the area of cosmology at a level, which might endanger the diversity of research performed in the Institute. This is the result of the hiring process, which is mainly out of control from IAP, the departure of key staff members and the award of long-term programs in the field of cosmology. On the other hand, the development of numerical simulations, both in personnel and computing power has reached almost the goal described in the last plan. Therefore, we can change this goal by a new one to maintain the diversity of research in IAP. The strong involvement of IAP in the Euclid mission is on line with the priority for wide-field Astronomy. But the contribution to the Euclid mission is not yet at the level required by our commitments, and we need to consolidate this participation. The priority should be modified accordingly. The priorities for this mid-term plan are therefore

- To be a center of excellence for extragalactic Astrophysics and Cosmology
- To be a place for strong collaboration between Astrophysics and theoretical Physics
- To develop studies in Exoplanets and the formation of planetary Systems
- To maintain a diversity of research domains
- To consolidate the IAP presence in large data processing centers related to IAP scientific priorities, especially for wide field astronomy
- To make the best use of existing large scale observatories, ground - or space - based

We here after summarize the main directions for each scientific field.

Exoplanets

With more than 800 exoplanets discovered, the field will evolve from a discovery phase to a characterization phase. The spectral analysis of the atmosphere of giant exoplanets will be one of the main directions of the research at IAP. In the short term, several large programs on ground based (GTC) and in Space, Hubble, have been accepted and will produce results in the coming years. New ground-based projects can be developed using the next generation of VLT instruments, SPHERE in particular. On a longer term, the main tools will become the E-ELT on the ground and the JWST in space. And later, a mission like ECHO, proposed to ESA as the M3 mission, will be dedicated to spectroscopy of planet atmospheres during the transit phase. IAP scientists have already a very visible contribution in this field, and are well involved in several of these future programs. This should continue to be a strong axis of research in the Institute.

While a large number of exoplanets have been discovered, the search for an Earth like planet or even a planet in the habitable zone continues. IAP is involved in 2 directions: the detection of exoplanets by microlensing, and radial velocity measurements. The first method has the capability to find planets in the habitable zone, even for solar type stars. The increased accuracy provided by the upgrade of existing spectrographs, or the new generation spectrographs like SPIROU at CFHT, or EXPRESSO at the VLT, combined with detection of planets by space mission like COROT, KEPLER or PLATO if selected by ESA, can also lead to the discovery of planets in the habitable zone. A third approach would be astrometry with the GAIA mission. IAP does not have expertise in this domain, and it seems better to focus on the core skills of the Institute: microlensing and radial velocity measurements.

The search for radio emission from exoplanets provides useful information on their magnetic field. Observations with GMRT have already produced interesting results, this program will be continued by enlarging the diversity of observed exoplanets and using new facilities like LOFAR which will provide high sensitivity at lower frequencies in mid-2013.

In the original plan, theoretical works on the proto-planetary disk and planets dynamical evolution completed these observational researches. Unfortunately, the leading person in this field has temporary left IAP, and we do not know how such studies can continue in the Institute, despite their strong interest.

Stellar Physics

The stellar Physics is a declining activity in IAP. This was already identified as a problem in 2007 during the preparation of the previous mid-term plan. Trials to attract a senior scientist who could create the conditions of a revival have failed, sometimes at the very last moment. For the next 5 years, there will be 2 activities: studies of high mass stars and the effect of fast rotation, and the data mining on the light curves obtained with the EROS-2 instrument. Both activities have links with the preparation of the GAIA mission.

Origin and Evolution of Galaxies

The research at IAP in this domain is mainly focused on the dynamical, morphological and spectro/photometric evolution of galaxies, inside or outside clusters. A large fraction of the works in the coming years will be based on the results of multi-wavelength surveys performed with ground based telescopes, like the CFHT, VISTA or the Sloan telescope and space observatories, mainly XMM/Newton, HST and Herschel. Several IAP scientists are involved in large surveys with these observatories, from nearby objects to galaxies at cosmological distances. For example, Ultra-Vista with ESO/VISTA, the deepest survey with this telescope, will provide insight on the stellar mass of very distant galaxies; KINGFISH with Herschel is the largest Herschel program on nearby normal galaxies, HERMES and ATLAS are deep surveys in the Far Infrared with Herschel that are used to trace the evolution of star formation with redshift, and will be a source of many interesting targets for ALMA follow-ups. BOSS, with the Sloan telescope, focuses on mapping the Universe on the largest scales, creating the largest volume three-dimensional map of galaxies ever created. These large programs and the other observation programs conducted by the people in the team will continue to feed the group with new data of high quality.

In parallel, efforts in modeling will continue with enhanced versions of existing packages for the spectral evolution of galaxies, including radiative transfer in the

ISM and for the morphological analysis to understand better the morphological evolution of galaxies, and the effect of the environment on this evolution.

A special attention will be given to the results of GAIA, mainly for the understanding of the dynamics of our Galaxy. An important goal at IAP is to work on semi-analytical models of disk formation compatible with the GAIA results. The shape and granularity of the dark matter halo will also been revisited after GAIA.

Cosmology and High Energy Astrophysics

The activity of this team will be focused on its main strengths: the physics of astrophysical relativistic jets and Gamma Ray Bursts, the physics of accretion on compact objects, the primordial nucleosynthesis and the chemical evolution of the Universe in a cosmological context, the detection and characterization of high redshift sources, and probing the distant universe by the emission or absorption properties of its components. This gives a lot of coherence to this group, as these topics are strongly connected: they relate to detect and characterize distant sources of high-energy radiation, to understand their physics, to use them as bright lighthouses to probe the physical conditions in the Universe at various redshifts and finally to model the cosmic evolution from the birth of the first stars to the present epochs. There are many collaborations within IAP between this team and others, especially in theoretical Physics, in large-scale structure studies, and in galaxy evolution.

The arrival of M. Volonteri (2012) has introduced a new field of research: the theory of the formation and growth of supermassive black holes, which is very complementary to the other activities of the group and will bring new interactions. Since 2012, J. Silk is also part of this team, with his ERC Advanced Grant dedicated to the study of Dark Matter. He will bring new ideas, new collaborations and people. This will strengthen the team, as well as the IAP as a whole.

The team will benefit from a favorable context for gamma-ray astronomy (Swift, Fermi, HESS and CTA) and from the development of multi-messenger astronomy. It is involved in the China-France SVOM space project to study Gamma Ray-Bursts and use them for cosmology, whose future is however still quite uncertain. The team is very active in carrying observations with the largest telescopes, especially VLT for quasar and GRB afterglow absorption spectra, as well as IRAM and ALMA for the studies of gas-rich galaxies.

Large Scale Structure and Deep Universe

This is the largest scientific domain of IAP by the number of people involved. The main strength of IAP is based on a combination of strong involvement in large projects in observational cosmology, the CFHT-LS in recent years, Planck now and Euclid in the future, together with a deep understanding of a number of topics: strong and weak gravitational lensing, non gaussianity in the CMB, and the dynamical evolution of large scale structure. These topics are also interleaved. For example, one IAP scientist is leading the studies of lensing effects on the CMB. The group has strong interactions with the theoretical Physics team on primordial cosmology. This joint expertise on observational cosmology and theory is an asset for IAP as a whole.

Numerical cosmology is now a vital tool to bridge theory and observation. During the past years, it has been possible to strength the sub-team working on cosmological simulations to reach a critical mass of 3 scientists and 1 engineer working mainly in cosmological simulations, collaborating with the others parts of the team. This activity will continue to be supported, and new developments are expected, for example by new hydrodynamic simulations and the studies of cool flows along the large-scale filaments.

This theme benefits from a long-term framework, with the participation in the Planck and Euclid space missions, the "Initiative de Cosmologie à Paris" (ICAP) funded by the ANR "Chaire d'Excellence" grant of Benjamin Wandelt, and the ERC DARK of Joe Silk. Moreover, the teams strongly benefits from the LABEX "Institut Lagrange de Paris" (ILP), a collaboration with two laboratories in the UPMC-CNRS, the LPNHE, and the LPTHE, plus the Institut Henri Poincaré, the Gabrielle Veneziano group at College de France and the Françoise Combes team at Paris Observatory.

All these facts place this domain in a healthy situation with long-term scientific and technical perspectives and a funding ensured by the space projects, the research grants and the Labex ILP

Theoretical Physics

By definition, it is more difficult to predict what will be the activity of this group of theoreticians than for the other parts of IAP, where the availability of long-term observational projects provides some guidelines for the future. Nevertheless, a list of future activities of this team is detailed in the appendix. We could stress that an increased collaboration between theoretical Physics and Astrophysics is expected after the publication of the first cosmological results from Planck in 2013, as well as during the preparation phase of Euclid, to derive observational signatures of a new theory that Euclid may detect. This is not the only domain where we expect progress. We can highlight possible variation of the constants in Physics, the detection of gravitational waves, and high-energy cosmic rays. All of these topics require strong interaction between the scientists across the Institute.

Observatory Tasks in the Framework of the OSU IAP

TERAPIX will continue at a low level to fulfill existing commitments with the CFHT (NGVS) and ESO (VISTA and VST programs). This requires already a 3-year contract (CDD) starting in early 2013. Beyond 2015, the future of TERAPIX should be discussed with INSU, taking into account the ramping up of Euclid at that time.

The PLANCK DPC activities should continue at the same level until the final delivery of the data in 2015.

The Herschel ICC activities will decrease after the end of the mission in March 2013. It will continue at a low level until the end of the post-operation phase for the next 5 years, as defined by ESA. A new CDD funded by CNES should join the team early 2013.

Euclid activities should have a strong increase in the 2 areas where IAP is expecting to have a leading role: the performance of the scientific ground segment and the data model on one hand, and the processing of the visible instrument (large CCD camera) data on the other hand. This ramping up requires new resources: software engineers, and astronomer positions. Part of these resources will come from the Planck Team, at the end of the scientific exploitation of Planck. However, the Planck mission extension makes the overlap between the 2 missions longer than expected and more difficult to solve.

SOPHIE activities will continue for several years, and might be replaced by other "Services d'Observation" (SO) like SPIROU at CFHT. However, François Bouchy, who is the leading person for this SO will leave IAP at the end of 2012. This will certainly decrease the role of IAP in this SO.

ECHO: IAP is participating in the ECHO proposal for the M3 mission. If selected, we will need to define what will be the participation of IAP in the SO that will be recognized by INSU as associated with this mission.

In addition to these SOs, IAP has proposed to INSU to recognize two other SOs: The constitution of a data base of all the QSOs, which will be identified in the BOSS survey, and the development and the maintenance of the ASTROMATIC open package, a set of astronomical software tools developed and maintained by Emmanuel Bertin.

Teaching

IAP will continue its contribution to teaching at the level of Bachelor's (Licence) and Master in the framework of the Physics Department of the UPMC. The main involvement of IAP as an Institute is of course at the Master level, and more specifically at the 2nd-year Master level (M2) for the specialty in Astrophysics. IAP will continue to provide classrooms for the M1 and M2 courses and facilities for software training in its premises. A secretary at IAP will provide the administrative support to the M2 student. Several members of the Institute will lecture in the M2 and an IAP-based professor will lead the M2 for the speciality in Astrophysics.

For the doctoral school, 5 teams of the IAP will remain associated to the "Ecole Doctorale d'Astronomie et d'Astrophysique d'Ile de France" (ED 127), in association with the Paris Observatory. The future of this "Ecole Doctorale" is still under debate, and depends strongly about what will be done at the other universities, Denis Diderot (Paris 7) and Paris Sud Orsay (Paris 11). The 6th team, the theoretical

Physics team will be attached to the ED of Physics at the UPMC (ED 107 for the time being).

The UPMC is willing to develop more international masters, using the teaching capabilities of the LABEXs. This is one of the challenges of the ILP. Looking at the scientific goals of the ILP, this international master should be directed toward cosmology, astroparticle, high-energy Physics and theoretical Physics. Such a project would have an impact on the existing M2 courses. Some care should be taken to ensure a non-damaging development of this an international master if created.

Outreach

2013 will be the 75th anniversary of the IAP. It is a good opportunity to raise the interest for the IAP, both from our support organizations and from the general public. Several events will be organized in the fall of 2013 targeted toward scientists, the media and the public.

The IAP will continue to maintain a high level of outreach activities. Monthly conferences will continue and we will ensure that their diffusion live on the TV Channel Canal-U extend beyond the test period in 2012. The LABEX ILP has also a strong component for outreach. This might create new opportunities that can be done in partnership with IAP. The European program Hands-on Universe will continue with IAP participation.

It should be noticed that the involvement of the IAP in these programs toward the children in school and toward the general public is already very large, requiring a strong involvement of whole the staff. It would not be possible to stretch them more to increase the level of outreach activities. But we will continue to support these activities at a high level; new initiative replacing previous activities, but at a constant level of personnel involvement.

The refurbishment of the IAP dome was included in the previous strategic plan. The plan included the installation of a small telescope to be used for master student training, for demonstration to schools and for event for the public like “La nuit des planètes” in partnership with the Paris Observatory. We failed to get the funds required, and nothing happened. Now, thanks to the Fondation del Duca award of Alain Lecavelier des Etangs, a high quality 10 cm wide field refractor with a set of day or night filters has been bought. It will be used primarily for eclipses campaign, but between it will be installed in the IAP dome and could be used for student training or outreach. This creates the condition for a new start of the original project. We will continue to seek funding for this operation.

Conclusion

An economist living on the 18th century has said that “les peuples sont la richesse des rois”. An alternate version more appropriate in our case is that the personnel is the asset of the research institutes. Nothing will be possible without the dedication of the staff, and the quality and the enthusiasm of the scientists. Fortunately, the IAP staff is exemplary. The unique and central position of IAP in the French astrophysics context makes the institute a very exciting place to work. With the present combination of long-term involvement in major projects and the academic freedom prevailing in our activities, the future of IAP appears to be secure, providing an adequate support from our funding agencies.