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ORIGINAL ARTICLE

Fundamental Problems in Astrophysics

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Abstract Progress of modern astrophysics requires the access to the electromagnetic spectrum in the broadest energy range. The Ultraviolet is a fundamental energy domain since it is one of the most powerful tool to study plasmas at temperatures in the 3,000–300,000 K range as well as electronic transitions of the most abundant molecules in the Universe. Moreover, the UV radiation field is a powerful astrochemical and photoionizing agent.

The objective of this review is to describe the crucial issues that require access to the UV range. A summary has been added to the end with a more classic view of UV needs by astronomical object type; this approach is followed at length in the rest of the contributions of this issue.

Keywords UV astronomy

1. Introduction

Access to the UV range is fundamental for the progress of astrophysics since UV spectroscopy is the most powerful tool to study plasmas at temperatures in the 3,000-300,000 K range. Also, the electronic transitions of the most abundant molecules in the Universe (H_2, CO, OH, CS, CO_2^+, C_2...) are in this range. Moreover, the UV radiation field is a powerful astrochemical and photoionizing agent.

The impact of UV instruments in modern astronomy can be clearly traced through the considerable success of the

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International Ultraviolet Explorer (IUE) observatory and successor instruments such as the GHRS and STIS spectrographs on-board the Hubble Space Telescope (HST), or the FUSE satellite operating in the far UV (90–120 nm range). Of particular importance has been access to high resolution $R \simeq$ 40,000–100,000 spectra providing an ability to study the dynamics of hot plasma and separate multiple galactic, stellar or interstellar spectral lines. Furthermore, the GALEX satellite is providing new exciting views of UV sources. As a result, UV facilities are in high demand; observing time on HST remains heavily oversubscribed (a factor ~6 in 2004), but its UV spectroscopic capabilities were hampered by STIS closure. Far-UV observations with FUSE also take a large share. This success has an interesting consequence: while astrophysicists world-wide are used to have a observatory-like access to the space telescopes working in this range, the BIG funding required to create/maintain large space facilities is driven by key scientific projects. The objective of this review is to describe briefly the crucial problems of modern astrophysics that require access to the UV range. A summary has been added to the end with a more classic view of UV needs by astronomical object type; this approach is followed at length in the rest of the contributions of this issue.

2. Crucial problems in modern astrophysics that require access to the UV range

Modern astrophysics is a mature science that has evolved from its early phase of discovery and classification to a physics-oriented discipline focussed in finding answers to fundamental problems ranging from cosmology to the origin and diversity of life-sustainable systems in the Universe. This evolution is not uniform; research in fields like compact objects or cosmology is clearly at this stage but the detection of extrasolar planets or the identification of the sources of γ-rays bursts are still at early stages. This diversity can be nicely traced in several recent collections of articles devoted to the identification of “unsolved problems in astrophysics” or to the “fundamental problems in astrophysics” (see, for instance, Bahcall and Ostriker, 1997). Though a much wider science case can be drawn, we have identified three key fields in astrophysics that cannot progress without easy and widespread access to modern UV instrumentation; these are:

1. Extrasolar planetary atmospheres and astrochemistry in the presence of strong UV radiation fields.
2. Chemical evolution of the Universe and the diffuse baryonic content.
3. The physics of accretion and outflow: the astronomical engines.

This list is by no means complete, but it certainly includes the most exciting and active problems that the majority of the astrophysical community would like to see solved. We detail each of these below.

2.1. Extrasolar planetary atmospheres and astrochemistry in young planetary disks

Since the mid 1990’s, more than one hundred extrasolar planets (hereafter called “exoplanets”) have been discovered. Since the unexpected discovery of the first hot-Jupiter extrasolar planet by Mayor and Queloz (1995), it is clear that exoplanets are an extremely diverse group. With the discovery of more than one hundred exoplanets, this diversity is clearly demonstrated by their orbital properties. We have “hot-Jupiters” with orbital periods as short as 3 days, and several “very hot-Jupiters” with orbital periods even shorter than 2 days but also exoplanets with periods of months to years. Less massive exoplanets have also recently been discovered (Santos et al., 2004; McArthur et al. 2004; Butler et al., 2004, Rivera et al., 2005), and the discussions on the true exoplanet nature show that a large variety is certainly possible.

The same variety is also expected for the atmospheres of these exoplanets. A quick look at the atmospheric content and history of the solar system’s inner planets shows that with four terrestrial planets, we find four very different possibilities: Mercury has almost no atmosphere, Mars’ atmosphere is tenuous with atmospheric pressure at ground level about one-hundredth that of the Earth, and Venus is the extreme opposite with more than ninety times the atmospheric pressure of the Earth with the same physical size of the planet. Note that Titan, although much smaller than the Earth, also has an atmosphere of 1.5 Bar and is very different from other giant planet satellites lacking atmospheres.

This diversity shows how difficult it is to predict what should be the content of an exoplanet’s atmosphere. In the solar system, the terrestrial atmosphere is unique with abundant O_2 and O_3 produced by biological activity though traces of O_3 have also been detected on the Jupiter’s satellite Europa. Another important characteristic of the terrestrial atmosphere is the significant amount of water. The Earth and Titan have both much N_2 in their atmospheres, but Titan contains more methane and no O_2. Mars and Venus have similar atmospheric composition, but they differ in total amount by a ratio of more than 10^4.

Thus, there is no simple answer to the question of the expected characteristics of planets and their atmospheres. The solar system planets provide a first hint of the expected diversity of the exoplanets and their atmospheres. Observations of exoplanets and the detailed characterization of their atmospheres will help us understand better the physical processes at work in the building of a planet and its atmosphere, and in the further evolution of such a system.

It is clear that the detailed processes that created the solar system planets are still a matter of debate and the impact of many processes must still be clarified. In short, we do not yet know the key physical parameters that govern the formation, evolution and fate of a given planet and its atmosphere.

How do properties such as effective temperature, stellar type, high-energy particle environment, and metallicity of the central star alter the evolution of its planetary system? What effects do a planet's orbital parameters (orbital distance and eccentricity) have on its size, mass and potential migration during the formation process? Are there volatile-rich planets like the proposed "Ocean-planets"? (Kutchner, 2003; Léger et al., 2004) How do interactions with other planets and planetesimals in their environment influence the evolution of a planet? This last question is undoubtedly related to the origin of water on the Earth. Are water-rich planets in the "habitable zone" common, rare, or exceptions?

Several processes believed to play key roles in building a planet can now be identified. To begin with, we can look at the best known planet, our Earth. Although still controversial, it is generally accepted that the Earth's original atmosphere was accumulated simultaneously with the planet's formation. However, the heating of the atmosphere by the young Sun's UV and X-ray flux, and the pressure of the strong solar wind at this period, led to the hydrodynamical escape of this primary atmosphere (as observed on HD 209458b in Ly$\alpha\lambda$1216Å, OIλ1305Å and CIIλ1330Å, Vidal-Madjar et al., 2003, 2004). Tectonic activity, volcanism and planet out-gasing then formed the secondary atmosphere in which we now live. Late bombardment by planetesimals in the young planetary system contributed a large fraction of the terrestrial water but the fraction of water originating from the Earth itself vs. the external contribution is still a matter of debate. Finally, photosynthetic plants enriched the atmosphere in O_2 and ozone, which are poisons to the first proto-life and are therefore considered as atmospheric bio-markers for advanced life forms. The observation of O_2 and ozone in the atmosphere of the Earth or of any exoplanet can lead to the conclusion that something very particular is happening there. This something could suggest the presence of life.

In the coming decade, several ground and space-based observing programs will lead to the discovery of an extremely large number of exoplanets, in particular, near-future space missions including Corot, Kepler or GAIA will discover large numbers of exoplanets transiting their parent stars. To acquire a revealing picture of these new worlds, we need to characterize the planetary atmospheres of a large sample of these exoplanets. The observation of UV and optical absorptions occurring when an exoplanet transits its parent star are a very powerful diagnostic technique; in fact, the most powerful technique for detecting Earth-like life-bearing planets because of the strong absorption of stellar UV photons by the ozone molecule in the planetary atmosphere (see Gómez de Castro et al., in this book). We cannot predict what will be discovered, but this will be an unprecedented opportunity to better understand the key processes at work in the shaping of planets and, in particular, to better understand the origin of our own Earth.

In addition, ultraviolet radiation plays a very important role in the evolution of the primary atmospheres of planetary embryos through photoionization and photochemical reactions (Watson et al., 1981; Lecavelier des Etangs et al., 2004). Thus, UV spectroscopy will allow the study of the interactions between the stellar UV field with the atmospheres and, as important, with the young planetary disks. Very recent chemical models are showing that the penetration of UV photons coming from the central engine in a dusty disk could produce an important change in the chemical composition of the gas allowing the growth of large organic molecules. In this context, UV photons at $\lambda > 1500$ Å photodissociating organic molecules could play a key role in the chemistry of the inner regions of the proto-planetary disk, while those photodissociating H_2 and CO would control the chemistry of the external layers of the disk directly exposed to the radiation from the star. The radiation field can produce a rich photochemistry on timescales shorter than the dynamical evolution time scales, leading to the formation of large carbon-rich molecules such as C_nH_2, $HC_{(2n+1)}N$, and C_n. Reactions between these species and H and H_2 may maintain their high abundances in spite of the strong radiation field emerging from the central star (see e.g., Cernicharo, 2004).

2.2. Chemical evolution of the Universe

The gas and stars are the dominant baryonic components of the Universe which can be understood in terms of a two-fluids system interacting through gravitation, starbirth and death; the massive stars life cycle controls the chemical enrichment of the Universe. Key parameters in the evolution of this system are the relative contributions to the energy and chemical input from the various possible sources to the gas phase (SNe, massive star winds and radiation fields, mass infall from the halo, galactic fountains and gas ejection in the intergalactic medium (IGM), galactic dynamics, cosmic rays and magnetic fields); also the roles of magnetohydrodynamical (MHD) turbulence and shocks in the energy cascade and structure formation need to be determined. During the last few years, a very efficient feed-back loop has been operating between radio observations and numerical simulations to study the role of MHD turbulence in the energy cascade within the densest regions of the galactic ISM (H I and molecular clouds). A similar feed-back loop needs to be established with UV observations to understand the heating/cooling processes and the overall thermal and dynamical evolution of the two-fluids system, including the formation of molecular clouds and massive stars clusters (starbursts). This loops needs to be established at two scales:

- *At galactic scale* where the details of the physics of the process can be tested. The dynamical evolution of the ISM concentrates cold matter in dense shells and filaments in the disk, while the halo acts as a pressure-release valve for the hot ($T > 10^{5.5}$ K) phase, thereby controlling its volume-filling factor. Here a large-scale fountain is set up by hot ionized gas injected from either the gas streaming out of the thick disk or directly from superbubbles inflated in the disk underneath. The gas then escapes in a turbulent convective flow enriching the halo with warm-hot gas. The detection of O VI, C IV and Si IV absorption in many High Velocity Clouds (HVCs) of our Galaxy indicates that they have hot, collisionally-ionized envelopes (Danly et al., 1992, Tripp et al., 2003). Understanding the ionization of such envelopes will constrain the properties of the Galactic corona and the Local Group medium. UV absorption lines are also the most sensitive probes for determining the abundances (and hence their Galactic or extragalactic origin) of the HVCs (see e.g., Richter et al., 2001). Note that the most robust specie for constraining the metallicity of HVCs is O I, since oxygen is only slightly depleted by dust grains (Moos et al., 2002) and the ionization potential of O I is very similar to that of H I. Thus, oxygen abundances based on the O I/H I ratio, depend only slightly on the ionization of the gas in substantially ionized plasmas.
- *At low redshifts ($z \sim 0.1$–0.2)* where it is feasible to resolve the starbursts and thus understand the violent star formation processes in galaxies and the variation of the Initial Mass Function (IMF) across the Universe. Because most of the massive stars form in starburst sites, starburst galaxies play a significant impact on the cosmic evolution of galaxies. Starbursts are responsible for the thermal and kinetic heating of the interstellar medium, and they are the factory where most of the heavy elements form. These elements are dispersed throughout the interstellar medium when massive stars explode as supernovae, and they can escape from the galaxy to the intergalactic medium through high velocity outflows generated by the violent star formation events occuring in these galaxies.

  UV observations are relevant not only because this range is very sensitive to the star formation history of galaxies, but also because it contains valuable tracers of the cold and warm phases of the ionized interstellar medium in starbursts that allow us to investigate the physics of the feedback and its consequences. Thus, high-spatial resolution UV spectra and imaging of nearby starbursts are crucial to further progress in understanding the violent star formation processes in galaxies, the interaction between the stellar clusters and the interstellar medium, and the variation of the IMF. High-spatial resolution spectra are also needed to isolate the light from the center to the disk in the UV luminous galaxies found by GALEX at $z = 0.1 - 0.3$. Observations at high spectral resolution ($R \geq 10000$) are required to isolate the galactic, the stellar and the interstellar components of several ions to perform a quantitative characterization of the outflows. A significant increase in spectral sensitivity ($\geq$10–100) with respect to HST + STIS is required to characterize superstellar stellar clusters of 10^5–10^6 $M_\odot$ beyond Virgo, nuclear starbursts at $z = 0.1$–0.2, and to probe the starburst galaxy environments out to tens of kpc using background quasars.

In addition, it is fundamental to map *the distribution and metallicity of diffuse baryonic matter and radiation in the Universe*. Independent of the different proposed models of the early Universe, the major baryonic component at $z < 3$ must be associated with the InterGalactic Medium (IGM). Recent studies suggest that the Warm-Hot Interagalactic Medium (WHIM) at low z contains more baryonic mass than stars and galaxies (Richter, 2005). These observations have been done in the UV with FUSE (the OVI triplet) and HST/STIS (broad Lyα absorption (BLA)) and imply cosmological mass densities of $\Omega_\mathrm{b}(\mathrm{OVI}) \simeq 0.0021 h_{70}^{-1}$ and $\Omega_\mathrm{b}(\mathrm{BLA}) \simeq 0.0027 h_{70}^{-1}$ (Sembach et al., 2004; Richter et al., 2004). These results have tremendous implications for our understanding of the intergalactic medium and galaxy formation.

Further out, looking into the past, the HeIIλ304Å effect provides the most sensitive tool to detect and analyzed the properties of the intergalactic medium. From theoretical modeling of the IGM we know that after the HI reionization, the IGM cools by expansion, is reheated by the delayed HeII reionization at $z = 3$, and continues to cool with decreasing redshift. Observations of the HeIIλ304Å forest over the redshift range $2.1 < z < 2.9$ will test this model in the most direct way. Besides observing the evolution of the mean IGM temperature, the characteristic scale of the density fluctuations of the IGM and its relation to the fluctuationg ionizing radiation field at a spatial resolution of less than 1 Mpc (comoving distance) will be observed (see Wamsteker et al., this book).

Spectroscopic observations of the HeIIλ304Å forest with HST and FUSE in two bright QSOs have shown that the HeII reionization phase of the universe ends at roughly $z = 2.9$ (Reimers et al., 1997), i.e., we observe a transition from optically-thick HeIIλ304Å absorption (the Gunn-Peterson trough) to a resolved HeII 304Å forest below $z = 2.8$. While FUSE was able to resolve the HeII 304Å forest in only two of the brightest high redshift QSOs in the sky (HE2347-4342, Kriss et al., 2001; HS1700 + 6416, Reimers et al., 2004), the true potential of these fundamental observations could not be exploited due to the very low S/N of the HeII FUSE spectra. Future observations of the HeIIλ304Å forest at high spectral resolution and better S/N have the potential to map both the intergalactic matter and radiation field in much detail.

Due to the possibility of observing HI and HeII simultaneously, the redshift range $2.1 < z < 2.9$ is the only cosmic epoch where the evolution of the fluctuating IGM can be compared in detail with predictions of theoretical models of large-scale structure formation. Knowledge of the shape of the ionizing UV background is also necessary for the determination of heavy element abundances in more than 90% of the baryonic component. The reason is that from the few ions observable from the ground (CIV, SiIV, OVI,...) the state of ionization and therefore, the element abundances cannot be determined quantitatively. Most of the relevant lines formed in the highly ionized component are in the intrinsic EUV at rest wavelengths between 300 and 900A (OIII-OV, NeIII-NeVII, SIII-SVI,....). The combination of HeIIλ304Å forest observations with high resolution EUV metal-line spectra and optical spectra of laboratory quality from 10m-class ground-based telescopes in a few strategic objects, such as HS $1700 + 6416$ with its rich metal line spectrum (Reimers et al., 1992), will lead to a more quantitative understanding of the evolution of matter composition, radiation field and structure formation in the strategic redshift regime between 2 and 3.

No further progress is feasible without high spectral resolution/high sensitivity UV spectroscopy.

2.3. Astronomical engines

Astronomical engines (stars, black holes, etc...) can accelerate large masses to velocities close to the speed of light or generate sudden ejections of mass as observed in Supernova explosions. They are also able to produce significantly milder winds, as seen in the Sun, or to eject gas shells induced by pressure pulsations in the stellar atmosphere. All of these phenomena transform energy of various forms (gravitational, thermal, radiative, magnetic) into mechanical energy to produce outflows in conditions very different than those tested in Earth laboratories. Mass ejections are hot, since a fraction of the mechanical energy involved in the acceleration heats the gas. The ejected matter is also diffuse, since it emerges from rarefied environments and the plasma confinement there is weak. Thus, the study of the thermal and kinetical properties of the ejected matter most astronomical engines need to be studied in the UV, with the only possible exception being very dense and slow outflows where molecules and dust can form.

The least conventional engines are those generating highly collimated bipolar outflows and jets. These are thought to be driven by a combination of gravitational energy, differential rotation and magnetic fields. They are among the most exciting objects in nature; however, their underlying physics is poorly known. This physical regime affects all of the many scales of Astrophysics; it determines the luminosity of the AGNs and the re-ionization of the Universe at $z \simeq 3$. It also determines the properties of planetary systems, which are just angular momentum reservoirs left over when the engine is turned off in pre-main sequence stars.

The physics of accretion-based engines, i.e., the way by which gravitational energy is transformed into radiation and mechanical energy (outflow) within accretion disks, is poorly known. Recently, linear instability analyses have demonstrated that keplerian hydrodynamical disks are stable; however, magnetohydrodynamic (MHD) disks are quite generally turbulent, and transport angular momentum outwards quite effectively. Thus, accretion disks ought to be magnetized in order to be turbulent and thus be able to dump gravitational energy into heat, as predicated in the standard α-disk model. After the recognition of this fact, accretion physics research is now focused on the study of the implications of magnetic fields both for the physics of the disks and for the disk interaction with the gravitational source. Today, this process is identified in many astrophysical objects spanning a range of 10^{10} in mass (from protostars, to white dwarfs, neutron stars, black holes and supermassive black holes). There are three common properties to all of these phenomena:

1. At very high energies, there is excess energy compared with the expected radiation from the central object and the thin accretion disk model.
2. When jets are generated, their velocity is similar to the keplerian velocity at the inner disk radius; e.g., ranging from a few hundred kilometers per second in protostars to velocities comparable to the speed of light in QSOs and micro-QSOs.
3. Violent ejections, eruptions, and rapid flux variations are detected. Knots are detected in the outflows, indicating that these contain a significant non-stationary component.

This physical behaviour applies to phenomena ranging from the formation of the Solar System, to interacting binaries, microquasars, Seyfert galaxies and quasars.

Gravity is the driving force in this process thus, the key to understand the underlying physics lies deep inside the gravitational potential well, in the interaction region between the dominant source of gravity (star, white dwarf, neutron star or black hole) and the inner disk. The radiative output from this region is produced in the UV-range for the vast majority of sources:

1. *In AGN's and microquasars* far UV radiation ($\lambda \sim$ 1500Å) is produced by the accretion disk, however UV

photons are energized to the X-rays range by inverse Compton scatering with the ambient highly relativistic electrons and the observed UV radiation is dominated by the reprocessing of the inner UV and X-ray photoionizing spectrum in the circum-nuclear matter: the gas clouds of the Broad Lines Region (BLR). As accretion is not stationary, the reverberation of the variations is observed in the UV range providing a powerful method to study the gas distribution around such sources allowing the determination of the characteristic scales and masses (e.g., Wandel, Peterson and Malkan, 1999; Kaspi et al., 2000).

2. *In accreting white dwarfs (WD)*, UV radiation is produced in the atmosphere of the accretion disk (and in the WD itself providing a useful tool to identify its characteristics). The propagation of the heating fronts generated in disk instabilities through the inner disk is tracked in the UV providing detailed information on the inner disk structure: disks seem to be strongly depleted during quiescence. The UV spectral energy distribution (SED) is crucial to asses temperature profiles and extension of the disk down to the magnetospheric radius in magnetized cataclysmic variables (CVs). Moreover, in magnetized CVs, the accretion flow is channelled by the field to the poles where the gravitational energy is released in a shock that heats the flow to 10^6–10^7K. These X-ray photons are reprocessed into the UV in the infalling gas column; thus UV monitorings allow tracking the shape and properties of the funnel.
3. *In T Tauri Stars (TTSs)*, UV radiation is produced in an extended magnetosphere, in accretion shocks alike the observed in accreting WD and in the outflow. Though many properties of the TTSs systems are alike the observed in WD, there are two fundamental differences: the central object is not compact and the accretion rate is controlled by the evolution of the accretion disk itself (instead of mass transfer from a companion star). It also adds an important extra motivation: understanding how dynamos are set in cool stars.

   In TTSs, the magnetic interaction between the star and the keplerian disk transforms angular momentum into magnetic field. Differential rotation in the disk, generates toroidal flux and the corresponding pressure push the field lines outwards and inflate them. The dissipation of magnetic energy through reconnection heats up the plasma to very high temperatures (see e.g. von Rekowski and Branderberg, 2005) producing a magnetosphere that extends up to 4-5R_* becoming a major contributor to the UV radiation flux. In a sense, the mediation of the magnetic field heats up the accretion process. This also have important implications for the radiative environment in protostellar disks and young planetary systems (see Gómez de Castro et al., 2006).

The most general physics controlling accretion-based engines is non-stationary and highly non-linear, since magnetic fields and relativity are involved. This implies an enormous mathematical complexity that can only be addressed in two manners: either by working with simplified models, or by designing good numerical experiments (which, in turn, require the simplified models to be properly understood). Thus, from the physics point of view, non-relativistic objects represent the very best laboratory to test our understanding of accretion.

Key questions that remain open concern:

1. What controls the efficiency of accreting objects as gravitational engines?, is the magnetic field needed to guarantee that outflows are fast?, what are the relevant timescales for mass ejection?
2. How does the accretion flow proceed from the disk to the source of the gravitational field in the presence of moderate magnetic fields?, which fraction of the gravitational energy lost in this process is deposited on the stellar surface?, which fraction is lost in amplification/dissipation of magnetic flux?
3. Which is the role played by radiation pressure in this whole process?
4. What role do disk instabilities play in the whole accretion/outflow process?, which are the key mechanisms driving these instabilities?

Though interacting binaries and AGNs have been studied by the main UV missions for many years there are still many problems to be studied because as our understanding of the underlying physics improves, new observations are required to test the improved theory (see Gaensicke et al., 2006; Kollatschny and Ting-Gui, 2006). A major breakthrough in our understanding of these objects will come from UV spectroscopic observations of the pre-main sequence systems because:

TTSs represent an intermediate class of objects, where the field plays a significant role but it is not as strong as observed in magnetic cataclysmic binaries or in neutron stars. Yet TTSs produce strong bipolar outflows and jets lasting a long fraction of their pre-main sequence evolution (from some 1000 years to 10^7 years) with velocities comparable to the keplerian velocity at 0.01 AU (or 2.1 $R\odot$). Thus, TTSs are the most efficient, accretion-based engines, in the non-relativistic regime.

As accretion progress, the configuration of the TTSs field evolves and the stellar dynamo sets-in. This evolution also provides fundamental information on how the solar dynamo was formed and evolved in the early phases.

A significant fraction of the radiation that keeps the gas ionized (and the field coupled to it) is produced by magnetic reconnection associated with the performance of the engine.

In addition, TTSs are unique to study the environment (radiation, high energy particles, dynamical processes) in which planetary systems, like ours, grow. Notice that recent theories proposed that the inner, Earth-like, planets begin to build-up some 10^6 after the star begin to form and, at this stage, the accretion-based engine is still operating. The radiation produced by the engine ougth to have an important effect on the inner disk evolution and the evaporation of the primary atmospheres of the planets-embryos.

As shown in Gómez de Castro et al. (2006), UV spectroscopy carried out with HST/STIS has shown that this work is feasible from observations of the brightest TTSs. The emission from the accretion flow in CIV, SiIII, CIII has been detected as the contribution of the wind to the CIII, SiIII, CII lines. High resolution spectroscopy with an instrument 20 times more efficient than HST/STIS will allow to reach the major factories of stars in the nearby Lupus or Taurus-Auriga complexes. An additional advantage of this improved sensitivity is that it will allow the carrying out of short-term variability studies; these are essential for studying properly the non-stationary components. This type of study has proven to be very valuable to distinguish the different sources of non-stationary phenomena such as flares or shocks (Gómez de Castro, 2002).

3. The ultraviolet Universe

In the following, a brief summary is presented on the major issues raised by the astronomical community when asked about whether and why access to the UV range is important for the progress of the various research fields in astrophysics. All these points are discussed at length in the subsequent articles of this special volume:

3.1. The solar system

Our Solar System serves as the nearest laboratory for planet formation and evolution and the detailed studies of its members are applied to the understanding of other, distant planetary systems. One of the basic questions in modern astrophysics is how planets "work", how planetary systems originated, and how life emerged on Earth. By studying the large and the small bodies in our system, we link "local" studies to the issue of the existence and properties of Earth-like extrasolar planets. UV observations, along with data collected in other spectral bands, are necessary and in some cases essential to understand the nature of our neighbours in the Solar System.

While many objectives of solar system research can be achieved by optical and near-IR (nIR) imaging, topics from surface mineralogic characterization to auroral activity require the combination of information spanning a wide spectral range including the UV.

Planetary studies require synoptic observations over periods of time ranging from a single revolution (hours to days) to many years (to span at least a full solar cycle). For a given aperture size, UV Astronomy from space can achieve much higher spatial resolution than from the ground because of the absence of the smearing effect of the Earth's atmosphere and because of the smaller diffraction limit of UV telescopes.

We identify two immediate programmatic requirements: the establishment of a mineralogic database in the ultraviolet for the characterization of planetary, ring, satellite, and minor planet surfaces, and the development and deployment of small orbital solar radiation monitors. The former would extend the methods of characterizing surfaces of atmosphereless bodies by adding the UV segment and permit the study of volatile transport on bodies with atmospheres. The latter are needed to establish a baseline against which contemporaneous UV observations of Solar System objects must be compared.

We identify two types of UV missions that would be two stages in a single process: one requires a two-meter-class telescope using almost off-the-shelf technology and could be launched in the next few years. The other requires a much larger (5–20 meter class) instrument that would provide the logical follow-up after a decade of utilizing the smaller facility. The very large UV telescope will offer angular resolution at par with that of the 100-m OWL telescope allowing coarse mapping much beyond the Kuiper-Edgeworth belt.

3.2. Cool stars

Emission in the UV is an essential probe for studying important physical processes related to the production and transport of magnetic energy in plasmas. Our understanding of such processes is closely related to our ability to predict the evolution of the solar magnetic activity and, therefore, to simulate the conditions in which life has evolved on Earth and how the solar emission of radiation will change due to the evolution of its magnetic dynamo. Future UV missions will advance the study of the consequences of stellar magnetic activity on planets orbiting around them.

Cool star atmospheres represent, undoubtly, a laboratory in which magnetic activity phenomena can be studied under a large variety of conditions, placing strong constraints on our knowledge of the fundamental processes involved. The consequences of both large and small magnetic activity can these be studied extensively. The UV range is unique as it permits the study of cool star atmospheres from the chromosphere to the corona using powerful diagnostics. Recent techniques have used the hydrogen Lyα line profile to study, for the first time, the wind from cool stars through its interaction with the interstellar gas (Wood, et al.,).

A 2m class UV telescope with high-resolution spectroscopy and monitoring capabilities would allow important discoveries in this field. A larger aperture telescope (from 4 to 6m) would permit the study of the plasma dynamics and the chromospheric – transition region structures of fainter magnetic active stars, like brown dwarfs and stars in clusters. This is requird to characterize the outer atmospheres of parent stars of extrasolar planets that will be discovered by future space missions like *COROT*, *Kepler*, and *Darwin*.

3.3. Massive stars

Massive stars and their descendants are important constituents of galaxies. Because of their high luminosities (up to $10^6\,L_\odot$) and their massive winds ($\dot{M} = 10^{-8}$ to 10^{-4} $M\odot\mathrm{yr}^{-1}$, $\mathrm{v}_\infty = 100$ to $2000\,\mathrm{km\ s}^{-1}$) they have an extremely important influence on the dynamics and energetics of the interstellar medium. They also enrich the interstellar medium in nuclear processed material. This enrichment occurs via mass loss (a massive star can lose 2/3 or more of its mass via a stellar wind) or during the SN explosion. They directly influence star formation by disrupting molecular clouds via SN explosions, or conversely they can initiate star formation through massive wind-blown bubbles and Sn shells compressing nearby molecular clouds. Massive stars are also thought to be responsible for the reionization of the early Universe. More recently, it has been proposed that the most massive stars are the progenitors of gamma-ray bursts.

The UV constitutes an optimum spectral window as the spectra energy distributions of massive stars reach their maxima within this wavelength range. Appart from this efficient coincidence established by nature, massive stars decorate the UV spectral region with a number of key diagnostics to our understanding of the nature of these objects and their interaction with the surrounding media.

High spectral resolution spectroscopy provides unique information about massive stars winds (P-Cygni profiles produced by the resonance transitions of CIV, NV, SiIV, OVI, etc). In addition, the unsaturated line profiles from ionized species trace very efficiently the mass-loss rate characterizing the stellar wind. Further, when combined with ρ^2 sensitive diagnostics at other wavelengths they may be used to calibrate the presence of inhomogeneities (“clumping”) in the wind.

The next step is to extend this work to external galaxies. The optimized spatial/spectral resolution achieved at UV wavelengths is fundamental for this purpose.

3.4. Star formation: From the ISM to planets

Planetary systems are angular momentum reservoirs generated during *star formation*. Solutions to three of the most important problems in contemporary astrophysics are needed to understand the entire process of planetary system formation:

The physics of the ISM. Stars form from dense molecular clouds that contain ∼30% of the total interstellar medium (ISM) mass. The structure, properties and lifetimes of molecular clouds are determined by the overall dynamics and evolution of a very complex system – the ISM. Understanding the physics of the ISM is of prime importance not only for Galactic but also for extragalactic and cosmological studies. Most of the ISM volume (∼65%) is filled with diffuse gas at temperatures between 3000 K and 300,000 K, best observed in the UV, representing about 50% of the ISM mass.

The physics of accretion and outflow. Powerful outflows are known to regulate angular momentum transport during star formation, the so-called accretion-outflow engine. Elementary physical considerations show that, to be efficient, the acceleration region for the outflows must be located close to the star (within 1 AU) where the gravitational field is strong. According to recent numerical simulations, this is also the region where terrestrial planets could form after 1 Myr. One should keep in mind that today the only evidence for life in the Universe comes from a planet located in this inner disk region (at 1 AU) from its parent star. The temperature of the accretion-outflow engine is between 3000 K and 10^7 K. After 1 Myr, during the classical T Tauri stage, extinction is small and the engine becomes naked and can be observed at ultraviolet wavelengths.

The physics of planet formation. Observations of volatiles released by dust, planetesimals and comets provide an extremely powerful tool for determining the relative abundances of the vaporizing species and for studying the photochemical and physical processes acting in the inner parts of the protoplanetary disks. This region is illuminated by the strong UV radiation field produced by the star and the accretion-outflow engine. Absorption spectroscopy provides the most sensitive tool for determining the properties of the circumstellar gas as well as the characteristics of the atmospheres of the inner planets transiting the stellar disk. UV radiation also pumps the electronic transitions of the most abundant molecules (H_2, CO,...) that are observed in the UV. See, for instance, the HST and FUSE observations of the Beta Pictoris disk which led to conclusion that CO is produced by an extremely large number of comets orbiting in this young planetary system (Jolly et al., 1998; Lecavelier des Etangs et al., 2001)

A rather modest UV telescope (2-m telescope with state-of-the-art optics, instruments and detectors) would produce an extraordinary scientific return as outlined above. A large, 50-m, UV-optical instrument would provide an efficient mean for measuring the abundance of ozone in the atmosphere of the thousands of transiting planets expected to be detected by the next space missions (GAIA, Corot, Kepler...). Thus a follow-up UV mission would be optimal for identifying Earth-like candidates.

3.5. Structure and evolution of white dwarfs and their interaction with the ISM

The development of far-UV astronomy has been particularly important for the study of hot white dwarf stars. A significant fraction of their emergent flux appears in the far-UV and traces of elements heavier than hydrogen or helium are, in general, only detected in this waveband or at shorter wavelengths that are also only accessible from space. Therefore, high-resolution far-UV spectroscopy has been essential for measuring white dwarf composition, to delineate the evolution of their atmospheres and to examine the relationship between the various physical processes that determine the appearance of these stars. In addition to highlighting photospheric material, the strong blue continua of hot white dwarfs also act as a backdrop to absorption lines from the interstellar medium. Consequently, observations of white dwarfs also provide an important probe of the interstellar space with which they interact, their progenitors supplying material and possibly accreting from interstellar clouds as they age. High-resolution spectra can also provide dynamical information on white dwarfs in binaries from which stellar masses can be estimated. UV imaging yields complementary information by resolving these systems, allowing direct detection of hot white dwarfs that might otherwise be hidden in the glare of much brighter companions at visible wavelengths.

Although white dwarfs have been studied in the far-UV throughout the past 25 years, since the launch of IUE, only a few tens of objects have been studied in great detail and a much larger sample is required to gain a detailed understanding of the evolution of hot white dwarfs and the physical processes that determine their appearance. Many outstanding problems remain, including the origin and relationships of the H and He-rich groups, the initial-final mass relation for white dwarfs and their progenitors and the 3D structure of the ISM. All white dwarfs that have ever been studied in the UV reside within our own galaxy and must have emerged from stellar populations with different ages and environments. To solve the outstanding problems and make significant further progress in the study of white dwarfs requires a substantial enlargement of the sample, to properly examine the full range of temperatures, gravities and possible environmental conditions by probing deeper into our own galaxy and extending studies to co-eval populations in globular clusters, the Magellanic clouds and nearby galaxies.

To achieve these goals there is a need for dramatically enhanced instrument sensitivity, providing high (R 50,000–100,000) and low resolution spectroscopy, with diffraction limited imaging. Coupled with advances in instrument and detector design, a 2-m class telescope would be able to address many of the science goals relating to observation of white dwarfs in our own galaxy, but in the time frame beyond 2015, it is absolutely essential that a large UV facility is constructed to reach outside the galaxy.

3.6. Interacting binaries

Interacting binaries (IBs) are among the most intriguing and exotic stellar systems, since the stellar components interact each other affecting their physical status and evolution. IBs consist of a variety of stellar objects in different stages of evolution and those containing accreting compact objects still represent a major challenge to our understanding of not only close binary star evolution but also of the chemical evolution of the Galaxy. These end-points of binary star evolution are showcases of wide variety of processes including mass accretion and outflow, stellar wind interaction with plasma conditions spanning a wide range of physical conditions including relativistic enviroments and extreme magnetic field strenghts. Consequently, IBs are also extremely versatile plasma physic laboratories.

Despite their great importance for a vast range of astrophysical questions, our understanding of close binary stars and their evolution is still very fragmentary. The ultraviolet is of outmost importance in the study of IBs, as a large part of their luminosity is radiated in this wavelength range, and, more importantly, as the UV hosts a multitude of low and high excitation lines of a large variety of chemical species. These transitions can be used both as probes of the plasma conditions, as well as tracers of individual components within the binary through time-resolved spectroscopy. Moreover, the physical status of the binary components and in particular the accreting white dwarf primaries in cataclysmic variables (CVs), symbiotic stars, and double-degenerate binaries can be easily isolated and studied in the UV range.

Even though substantial scientific progress has been achieved throughout the last three decades, primarily using the International Ultraviolet Explorer (IUE), the Hubble Space Telescope (HST), and the Far Ultraviolet Spectroscopic Explorer (FUSE), there are still many open problems. Among them, key issues are: (i) the nature of SNIa progenitors exploring both single and double-degenerate channels, (ii) the physics of accretion discs, in particular the role of viscosity and its time-dependence, and the development of winds, (iii) the fundamental properties of white dwarfs in CVs, as these are strongly affected by accretion and its associated angular momentum and (iv) the nature of the IB population in globular clusters. These can be efficiently achieved by means of UV observations surveying much larger samples than done so far. In particular the first three goals require medium ($R \simeq 2000$) to high ($R \simeq 20000$) FUV (possibly down to 912 Å) resolution spectroscopy with high temporal resolution capabilities (time-tag) to allow phase–resolved studies along the binary orbit as well as with a high duty cycle to monitor outburst evolution. The latter goal instead requires a large (10 arcmin) field-of-view imager with diffraction–limited spatial resolution using broad band FUV and NUV filters with accurate timing capabilities.

A large collecting area is relevant to deeply investigate fast UV variability which is an ubiquitous feature in IBs. Fast non-periodic and quasi-periodic variations on timescales from seconds to tens of minutes are commonly observed in CVs. Quasi-periodic-oscillations (QPOs) of a few seconds were discovered in the optical in the eighties and in the UV range in the early nineties in a few bright strongly magnetized CVs. They are believed to arise from shock oscillations though the driving mechanism is still unclear. A proper knowledge of their energy distribution and of the variations of amplitudes and phases is of great potential to diagnose the magnetic field and cooling process in the radiative shocks. Furthermore, oscillations during dwarf novae outbursts (DNOs) and QPOs from a few seconds to thousands of seconds were detected for the first time in the UV and now have been recently recognized as parallel to the high- and low-frequency QPOs observed in X-ray binaries (Warner, 2004) with an origin likely residing in the magnetic nature of the accreting white dwarf. Also, flickering on timescales of minutes are believed to be associated to fluctuations in the mass accretion.

3.7. Active Galaxies

Active Galaxies emit their maximum flux in the UV/FUV. The overall continuum flux peaks in-between the optical and soft X-ray spectral range. More than half of the bolometric luminosity of an (un-obscured) AGN is emitted in this big blue bump. Models of hot accretion disks – surrounding the central super-massive black hole in AGN – cannot reproduce in a simple way the observed spectral shape.

This rest frame EUV continuum of highly redshifted AGN is important for our understanding of the evolution of the early universe. The UV continuum of quasars ionizes the intergalactic medium at the end of the dark ages.

Furthermore, the central continuum source in AGN ionizes the circumnuclear gas in the so called broad line region (BLR) and narrow line region (NLR). The overall continuum distribution as well as the UV spectral lines (narrow emission lines, broad emission lines, absorption lines) are tracers of the physical conditions of those regions where these emission lines originate. Most important diagnostic lines for studying the physical conditions and metallicities in the central regions of AGN are emitted in the UV. It is possible to derive some information for distant ($z \geq 2$) as well as luminous quasars when the diagnostic lines are shifted into the optical range with ground-based telescopes. But it is necessary to observe the UV-spectra of 'nearby and present-day' AGN for studying their cosmological evolution as well as the evolution of the universe. The UV spectra of the class of low luminous AGN can be observed only in the local universe because of their faintness.

The emission line region of the narrow lines is spatially resolved in some nearby objects. They originate at distances of pc to kpc from the central ionizing source. However, the broad emission lines originate at distances of light days to light months only from the central ionizing source. This BLR is unresolved by orders of magnitudes even for the nearest AGN. But variability studies of the ionizing continuum flux and the emission line intensities/profiles give us information on the structure and kinematics of the surrounding of the central supermassive black hole in AGN as well as on their mass itself. The monitoring of highly ionized UV lines in AGN enables us to study the physics of the immediate environment of black holes nearest to the center.

3.8. Starbursts

Starbursts are systems with very high star formation rates per unit area. They are the preferred places where massive stars form, the main source of thermal and mechanical heating in the interstellar medium, and the factory where the heavy elements form. Thus, starbursts play an important role in the origin and evolution of galaxies. The similarities between the physical properties of local starbursts and high-z star-forming galaxies highlight the cosmological relevance of starbursts. On the other hand, nearby starbursts are laboratories for studying violent star formation processes and their interaction with the interstellar and intergalactic media, in detail and deeply. Starbursts are bright at ultraviolet (UV) wavelengths, as they are in the far-infrared, due to the 'picket-fence' interstellar dust distribution. After the pioneering IUE program, high spatial and spectral resolution UV observations of local starburst galaxies, mainly taken with HST and FUSE, have made relevant contributions to the following issues:

- *The determination of the initial mass function (IMF)* in violent star forming systems in both, low and high metallicity environments, and in dense (e.g. in stellar clusters) and diffuse environments: A Salpeter IMF with high-mass stars constrains well the UV properties.
- *The modes of star formation*: Starburst clusters are an important mode of star formation. Super-stellar clusters have properties similar to globular clusters.

- *The role of starbursts in AGN*: Nuclear starbursts can dominate the UV light in Seyfert 2 galaxies, having bolometric luminosities similar to the estimated bolometric luminosities of the obscured AGN.
- *The interaction between massive stars and the interstellar and intergalactic media*: Outflows in cold, warm and coronal phases leave their imprints on the UV interstellar lines. Outflows of a few hundred km s^{-1} are ubiquitous phenomena in starbursts. These metal-rich outflows and the ionizing radiation can travel to the halo of galaxies and reach the intergalactic medium.
- *The contribution of starbursts to the reionization of the universe*: In the local universe, the fraction of ionizing photons that escape from galaxies and reach the intergalactic medium is of a few percent. However, in high-z star-forming galaxies, the results are more controversial.

Despite the very significant progress over the past two decades in our understanding of the starburst phenomenon through the study of the physical processes revealed at satellite UV wavelengths, there are important problems that still need to be solved. High-spatial resolution UV observations of nearby starbursts are crucial to further progress in understanding the violent star formation processes in galaxies, the interaction between the stellar clusters and the interstellar medium, and the variation of the IMF. High-spatial resolution spectra are also needed to isolate the light from the center to the disk in UV luminous galaxies at $z = 0.1$–0.3 found by GALEX. Thus, a new UV mission containing an intermediate spectral resolution long-slit spectrograph with high spatial resolution and high UV sensitivity is required to further progress in the study of starburst galaxies and their impact on the interstellar and intergalactic media.

3.9. Supernovae (SNe)

UV observations of SNe are required not only for understanding of the SN phenomenon itself, such as the kinematics and the metallicity of the ejecta, but also for providing exciting new findings in Cosmology, such as the tantalizing evidence for "dark energy" that seems to pervade the Universe and to dominate its energetics. SNe are bright events that can be detected and studied even at very large distances. Ultraviolet spectroscopy is crucial in order to:

Study the metallicity of individual SNe
Study the metallicity of the intervening ISM/IGM
Study the kinematics of the fast moving (i.e. the outermost layers) of the ejecta through the analysis of strong UV lines with P-Cygni profiles.
Study the overall energetics of SNe explosion at early phases (from shock breakout to optical maximum for types of SNe, but most importantly for all Type II SNe)
Study of the strong emission lines produced in the interaction of the ejecta with pre-SN circumstellar material, e.g. NV 1240 Å and collisionally excited CIV 1550 Å, NIV] 1470 Å, OIII] 1665 Å, NIII] 1750 Å, CIII] 1908 Å.

SNIa are very good standard candles (e.g. Macchetto and Panagia, 1999) to measure distances to distant galaxies, currently up to redshift $z \simeq 1$ and, considerably more in the foreseeable future. This is a challenging proposition, both for technical reasons (observations in the near IR of increasingly faint objects) and for more subtle reasons, i.e. one must verify that the discovered SNe are indeed SNIa and that these SNa share the same properties of their local Universe relatives. One can only discern Type I from Type II SNe on the basis of the overall properties of their UV spectral energy distributions (Panagia, 2003, 2005).

4. Summary

This review outlines the scientific reasons behind the need for an ultraviolet observatory. Most of science described here could be carried out with two basic instruments:

1. A high-resolution (50,000–100,000) spectrograph covering the whole 90–320 nm spectral range.
2. A low-spectral resolution (1000–5000) high-sensitivity spectrograph allowing integral field spectroscopy (long-slit in its simplest version) with spatial resolution (50 mas) and wavelength coverage from 110–450 nm.

These instruments should provide an improvement by a factor of ∼20 in effective area over the HST/STIS capabilities. This improvement is rather conservative from the technological point-of-view since it could be achieved by improving optical designs and coatings and make use of MCP detectors with enhanced sensitivity, bigger size and improved dynamic beeing related to new fast read-out electronics. It is amazing the large progress that could be achieved with a relatively modest investment; a good example of this is the proposed*World Space Observatory* project.

Looking into the far future, it is clear that the frontier is building larger facilities that increase the effective collecting surface by, at least, 2 orders of magnitude. A properly instrumented 4–6 m telescope in space would be very useful for future UV observations.

A larger, 20 m size, telescope in space represents a huge technological defy. Coordinated constellations of 1-m size telescopes seem to be the most realistic manner to get large collecting surfaces. In turn, this would allow carrying out UV interferometry. The potential of high spatial resolution (milliarcsecond scale) instruments is enormous. One promising concept to get micro-arcsecond resolution imaging is the Stellar Imager mission under study at NASA GSFC, a kilometer scale interferometer composed of around 30 small telescopes formation, flying in space (Carpenter et al., 2004).

Another possibility would be building large ground-based telescopes in ozone depleted areas. The discussion of the 'ozone hole' due to human activity on the one hand, and the realization that photon absorption by ozone in the UV is one of the important sources of opacity in the atmosphere, would argue that the location of a ground-based telescope underne ath an ozone hole may extend the spectral range accessible from the ground into the UV. Assuming this effect to be present and significant, the best place for such a ground-based UV telescope would be in the Antarctic, possibly at the Concordia station at Dome C. This location shows the best seeing for any Earth based observatory, but as far as we are aware no long-term study of the atmospheric transparency at short wavelengths has been conducted there. The study should also consider the atmospheric emissions at a location relatively close to the South Magnetic Pole, and the influence of sunlight scattered into the telescope when the Sun is below the horizon.

A detailed accounting on the scientific requirements to UV observatories can be found in Kappelmann et al. contribution to these proceedings.

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