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THE EFFECT OF RAM–PRESSURE STRIPPING ON GALAXY PROPERTIES, IN A HYBRID MODEL FOR GALAXY FORMATION IN CLUSTERS

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High-resolution N–body simulations of massive dark matter halos have been combined with semi-analytical modeling, to study galaxy formation and evolution in clusters. Preliminary results about the effect of ram–pressure stripping are presented.

1 The model

Cluster environment appears to be the most suitable laboratory for studying how dynamical processes affect galaxy properties. In fact, galaxy encounters are more frequent in clusters, and they can lead to full mergers or to galaxy "harassment", thus possibly changing spiral galaxies into ellipticals or lenticulars. Moreover, the high efficiency of ram–pressure stripping against the diffuse intra–cluster medium can remove a substantial amount of gas from galaxies, and may contribute to modify the morphology, as well as the star formation rates, the luminosities and the colors of the cluster population.

To address this issue, we are studying galaxy formation in clusters by means of a so–called "hybrid model", combining N–body simulations that follow the formation and merging history of DM halos, and a semi–analytical model that describes the physics of the baryonic component. In fact, under the hypothesis that dark matter (DM) is the dominant component of the Universe, and that massive structures form hierarchically from mergers of smaller objects, DM halos form first, and galaxies form and evolve within, and with them.

In this picture, clusters of galaxies are hosted by very massive DM halos, that derive from the assembly of smaller structures during the evolution of the Universe. To follow their formation history in as many details as possible, we have therefore re–simulated at high resolution a sample of 10 very massive DM halos, 5 of $\sim 10^{14}\,\mathrm{M}_\odot$, and 5 of $\sim 10^{15}\,\mathrm{M}_\odot$. The sample has been selected from the "Very Large Simulations" (Yoshida & The Virgo Consortium 2000), with a ΛCDM cosmology ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$), and a particle mass of $6.86\ 10^{10}\ \mathrm{M}_\odot/h$, To resimulate the selected halos at higher resolution, we have produced the suitable new initial conditions using the technique by Tormen, Bouchet & White (1997), and we have run the new simulation with the tree code "GADGET" (Springel, Yoshida & White 2000). The mass resolution has

been increased by a factor ~ 33, so that DM halos of $\sim 2\,10^9\,\mathrm{M}_\odot/h$ (a minimum of 10 particles) can be resolved. Thanks to this technique, we get the original 10 massive halos and their whole formation history in much more details, and we can therefore describe galaxy evolution in a more reliable way.

This is done in the framework of the semi–analytical modeling, where gas cooling within DM halos, star formation, energy feedback from supernova, merger of galaxies, and all the processes acting on the baryonic component are described by means of simplified analytical formula (e.g., Kauffmann, White & Guiderdoni 1993; Cole et al. 1994; Somerville & Primack 1999; Kauffmann et al. 1999). The model we use is called "GALICS" (Galaxies in Cosmological Simulations; Hatton et al. 2000). It is similar in many respects to other models of this kind, but it also presents some improvements and changes.

In particular, we have also included the description of gas stripping from discs because of the ram–pressure against the intra–cluster medium. This has been done following the original idea of Gunn & Gott (1972) and using simplified assumptions. To derive the amount of cold gas stripped by ram–pressure, we compute the stripping radius as:

$$\frac{R_{\mathrm{str}}}{R_{\mathrm{d}}} = -\ln\sqrt{\frac{\rho_{\mathrm{ICM}}(r)\,v_\perp^2}{2\,\pi\,G\,\Sigma_{0\star\mathrm{g}}\,\Sigma_{0\mathrm{g}}}}, \qquad (1)$$

where R_{d} is the characteristic radius of the gas and gas-plus-stars distributions in the disc, assumed to have an exponential profile of central surface brightness $\Sigma_{0\mathrm{g}}$ and $\Sigma_{0\star\mathrm{g}}$, respectively; $\rho_{\mathrm{ICM}}(r)$ is the intra–cluster medium density at the orbital position r of the galaxy; $v_\perp$ is the component of the galaxy velocity perpendicular to the disc.

In the next section, the luminosity function, the morphological fractions, and the average colors of cluster galaxies derived with the dynamical friction and the satellite–satellite mergers only (df-ss), are compared to those obtained by including also the ram–pressure stripping (df–ss–rp). As an example, we show the results obtained for one of the most massive DM halos, having a virial mass of $M = 1.65\,10^{15}\mathrm{M}_\odot/h$. The results are preliminary, but they already show that this dynamical process, usually neglected in semi-analytical models, can instead have interesting and important effects on galaxy properties.

2 Results

The comparison between the resulting luminosity functions is presented in figure 1, where the black dotted histogram refers to the first case (df–ss), and the red one to the case with ram–pressure included (df–ss–rp). Ram–pressure stripping mainly affects the faint end of the luminosity function, decreasing the number of faint objects. In fact, gas stripping is more efficient in small discs, where the binding energy is lower. Star formation is therefore particularly reduced

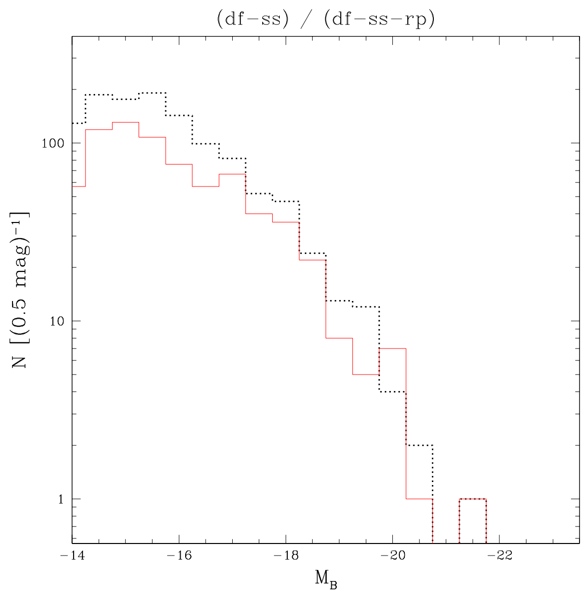

Figure 1: Luminosity function of cluster galaxies in the B band. The black dotted histogram refers to the case with dynamical friction and the satellite–satellite mergers only (df-ss), the red one to the case when also ram–pressure stripping is taken into account.

in these objects, which disappear from the sample (selected at $M_B < -14$), and make the faint end of the luminosity function flatter.

We have also investigated how ram–pressure stripping affects galaxy morphology. Galaxies have been classified by their bulge–to–disc luminosity ratio in the B–band, following Simien & de Vaucouleurs (1986). Defining $T \equiv \exp(-L_B/L_D)$, so that $T = 1$ for a pure disc and $T = 0$ for a pure bulge, the different morphological types correspond to the following intervals of T: $T \leq 0.219$ for elliptical galaxies; $0.219 < T < 0.507$ for lenticulars; $T \geq 0.507$ for spirals if galaxies are brighter than $M_B = -17$; $T \geq 0.507$ for dwarf/irregulars if galaxies are fainter than $M_B = -17$.

The cumulative fraction of morphological types for galaxies brighter than a given magnitude M_B are plotted in figure 2, where the black lines refer to the df–ss case, the red ones to the case with ram–pressure also included. Almost no difference is found for the population of galaxies brighter than $M_B \simeq -17.5$. If fainter galaxies are also considered, the effect of ram–pressure stripping is to slightly increase the fraction of ellipticals and S0, and to decrease the number of dwarf/irregulars. In any case, the differences are always small, of the order of 5%. More interesting is its effect on galaxy colors. The mean B–V color of cluster galaxies, together with the corresponding scatter plot, is shown in figure 3 as a function of the absolute B magnitude. As before, black and red refers respectively to the cases without and with ram–pressure. Two main effects of the ram–pressure stripping can be recognized: it reddens by 0.1–0.15 magnitudes all galaxies fainter than $M_B = -19$, and it tightens significantly the color–magnitude relation, eliminating almost all galaxies bluer than B–V = 0.7. Subtracting a fraction of cold gas from the discs, decreases the possibility of forming new (blue) stars. If ram–pressure stripping is considered, the stellar population is therefore redder and more uniform, on average. Moreover, most of the faint blue discs that thicken the color–magnitude relation in the case without ram–pressure, disappear from the sample if ram–pressure stripping is taken into account, since their star formation is reduced and they do not become luminous enough.

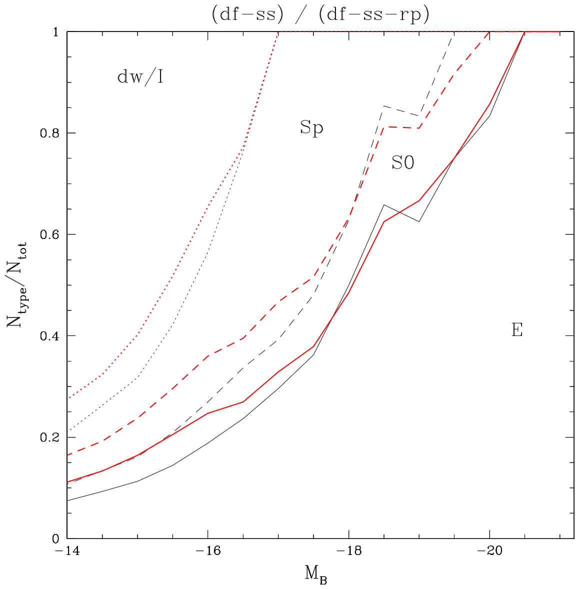

Figure 2: Cumulative morphological fractions in clusters, for the case without (black lines) and with (red lines) ram–pressure stripping. Solid lines correspond to the fraction of ellipticals with respect to the total number of galaxies brighter than the value of M_B marked on the x axis. The same, but for the fraction of elliptical plus S0, and for the fraction of ellipticals plus S0 plus spirals, are shown by the dashed and dotted lines, respectively. The percentage of "dwarf/irregulars" is given by 1 minus the values corresponding to the dotted lines.

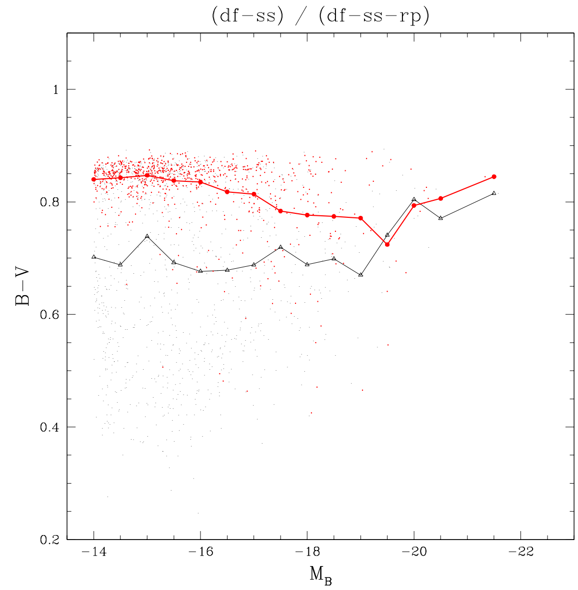

Figure 3: B–V color of cluster galaxies as a function of the absolute B magnitude, for the case without (black) and with (red) ram–pressure stripping. Dots show the scatter plot, lines are the average colors in bins of 0.5 magnitudes.

Conclusions

Hybrid models are very useful tools for studying galaxy formation and evolution. The possibility of switching on/off one or more physical processes allow to estimate their role in determining galaxy properties. As an example, we have investigate what is the effect of ram–pressure stripping in cluster environment. We have shown that this process mainly affect galaxy luminosities and colors, fading and reddening the cluster population. Also morphological types are slightly affected, with the fraction of ellipticals and lenticulars increasing with respect to the case without ramp–pressure stripping.

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