Building a control sample for galaxy pairs

Josefa Perez[1,2], Patricia Tissera[1], Jeremy Blaizot[3]

[1] *Instituto de Astronomía y Física del Espacio,Conicet-UBA, CC67, Suc.28,Ciudad de Buenos Aires, Argentina.*
[2] *Facultad de Ciencis Astronómicas y Geofísicas, Universidad Nacional de La Plata, Argentina.*
[3] *Université de Lyon, Lyon, F-69003, France ; Université Lyon 1, Observatoire de Lyon, 9 avenue Charles André, Saint-Genis Laval, F-69230, France*

18 June 2009

ABSTRACT

Several observational works have attempted to isolate the effects of galaxy interactions by comparing galaxies in pairs with isolated galaxies. However, different authors have proposed different ways to build these so-called control samples (CS). By using mock galaxy catalogues of the SDSS-DR4 built up from the Millennium Simulation, we explore how the way of building a CS might introduce biases which could affect the interpretation of results. We make use of the fact that the physics of interactions is not included in the semianalytic model, to infer that any difference between the mock control and pair samples can be ascribed to selection biases. Thus, we find that galaxies in pairs artificially tend to be older and more bulge-dominated, and to have less cold gas and different metallicities than their isolated counterparts. Also because of a biased selection, galaxies in pairs tend to live in higher density environments, and in haloes of larger masses. We find that imposing constraints on redshift, stellar masses and local densities diminishes the selection biases by $\approx 70\%$. Based on these findings, we suggest observers how to build an unique and unbiased CS in order to reveal the effect of galaxy interactions.

Key words: cosmology: theory - galaxies: formation - galaxies: evolution - galaxies: interactions.

1 INTRODUCTION

Galaxy interactions have been found to drive strong changes in the physical properties of galaxies. Their effects on galaxy properties such as star formation, morphology, metallicity have been largely studied in optical (e.g. Larson & Tinsley 1978; Donzelli & Pastoriza 1997; Barton, Geller & Kenyon 2000, Kewley et al. 2006) and infrared observations (e.g. Sanders & Mirabel 1996; Lin et al. 2007; Geller et al 2006). Numerical simulations have provided insights on the relevance of mergers and interactions in the formation and evolution of galaxies (Toomre & Toomre 1972; Barnes & Hernquist 1992; Mihos & Hernquist 1996), principally in a hierarchical clustering scenario (e.g. Tissera 2000; Somerville et al. 2001; Perez et al. 2006).

With the aim to isolate the effects of interactions, it has become popular to build CS to confront the properties of galaxies in pairs. Lin et al. (2007) found that the infrared luminosity of blue merging galaxies and kinetically close pairs (for a given stellar mass) almost duplicates the infrared luminosity of CS randomly drawn from blue isolated galaxies. Using spectroscopy and infrared photometry, Geller et al. (2006) found a strong correlation for galaxy pairs between the Balmer decrement and the H-K colour, which indicates that there is an intrinsic reddening associated to the near

infrared emission of hot dust present in tidally triggered-star forming regions. They also show that the near infrared colour diagram is a good indicator of interaction effects, with a larger dispersion in the H-K colours for galaxy pairs than for control galaxies. Even more, they found that this dispersion in the NIR colour diagram for galaxy pairs increases for smaller relative projected separations. In the optical, De Propris et al. (2005) showed that interacting galaxies in the Millennium Galaxy Catalogue tend to be marginally bluer than non-interacting galaxies. They also found that galaxy pairs have a larger contribution of very early and very late type objects with respect to their control galaxies. They interpreted these facts as the result of the action of mergers and interactions on the triggering of star formation and morphology evolution.

Large galaxy surveys such as the 2dF Galaxy Redshift Survey (2dFGRS., Colless et al. 2001) and Sloan Digital Sky Survey (SDSS, York et al. 2000) allow a statistical and comprehensive study of different properties (i.e. star formation activity, morphology) for galaxies with and without a close companion. Close interactions at low relative velocity have been found to trigger significant star formation activity (e.g. Lambas et al. 2003; Nikolic et al. 2004; Luo et al. 2007; Li et al. 2008). In fact, the mean specific star formation rate of

galaxy pairs with projected separations lesser than $\sim 30\,\mathrm{kpc}$ is significantly enhanced over the mean value corresponding to galaxies without a close companion, inhabiting similar environment (Lambas et al. 2003; Alonso et al. 2004; Alonso et al. 2006). It has been also found that galaxy interactions might induce star formation in all environments (Alonso et al. 2004; Li et al. 2007). In addition, the analysis of colours for galaxies in pairs shows that, although close pairs have a larger fraction of blue galaxies, they also exhibit an excess of red galaxies with respect to those systems without a close companion located in regions of similar densities (Alonso et al. 2006). While the blue excess is associated to systems with intense star formation triggered by the interaction, the red one could be related to an old dominating stellar population or to the result of dust stirred up during the encounter which could hide part of the current star formation activity.

The reliability of these outcoming results depends on the details of the construction of these CS used for comparison. Different authors resorted to different way of building up CS with the aim at isolating the effects of interaction. Barton et al (2007) noticed that galaxies in close pairs reside preferentially within cluster or group-size haloes, representing a biased population, not suited for direct comparison to field galaxies. In order to isolate the effect of interactions, these authors suggest a construction of a clean pair sample built with galaxy pairs which are isolated in their dark matter haloes and, for comparison, a control sample populated only with one isolated galaxy in the halo. Lambas et al. (2003) removed galaxies in groups and clusters from the 2dFGRS by cross-correlating the catalogue with the groups sample of Merchan & Zandivarez (2002), before selecting galaxies in pairs and in the control sample. However, a comprehensive study of the possible biases that could affect the results is still missing.

In this paper, we use a mock galaxy catalogue of the SDSS-DR4 to carry out a global study of biases which could arise in the selection of control galaxies and to suggest how to build an unique and unbiased CS to isolate the effect of interactions. The comparison with observations will be carried out in a separate paper.

The galaxy pair catalogue studied in this paper was built up from a mock catalogue of the SDSS-DR4 constructed from the galaxy sample generated by the semi-analytic model (SAM) of De Lucia & Blaizot (2007) applied to one of the largest N-body cosmological simulation, the so-called Millennium Simulation. The SAM does not include the physics of interactions, hence, when selecting pairs and CS, any difference in their properties cannot be attributed to interactions but to the constraints used to build the CS. We will make profit of this fact to obtain the criteria to build up a proper CS which univocally allows the individualization of the effects of interactions.

This paper is organized as follows. Section 2 describes the semi-analytical model used to build the mock galaxy catalogues from where the galaxy pair and control samples are selected. The analysis of different bias effects in the selection of CS is shown in Section 3. In Section 4, we discuss how to correct these biases in order to build a suitable CS. We suggest the observers how these findings could be taken into account in real surveys. An example of this procedure is shown in Section 5, where we use the theoretical analysis of the mass-metallicity relation to infer possible biased results from observations. Conclusions are summarized in Section 6.

2   MOCK GALAXY PAIR CATALOGUE.

We use the catalogue of galaxies built up by De Lucia & Blaizot (2007) from the Millennium Simulation (Springel et al. 2005). This simulation describes the evolution of the dark matter component assuming a ΛCDM cosmology with cosmological parameters determined from the combined analysis of the 2dFGRS (Colless et al. 2001) and the first year WMAP data (Spergel et al. 2003): $\Omega_m = 0.25$, $\Omega_b = 0.045$, $\Omega_\Lambda = 0.75$, $H_0 = 100\,h$, $h = 0.73$, $n = 1$ and $\sigma_8 = 0.9$. The Millennium Simulation follows $N = 2160^3$ particles with mass $8.6 \times 10^8 \mathrm{h}^{-1} M_\odot$ within a comoving periodic box of $500\mathrm{h}^{-1}\mathrm{Mpc}$ on a side. In a large simulation like the present one, a rich substructure of gravitationally bound dark matter subhaloes is found to orbit within larger vitalized haloes. Then, the identification of substructure is a complex process which required sophisticated tools specially designed to select subhaloes within larger haloes in an efficient way (Springel et al. 2001). After a gravitational binding analysis, only bound substructures with more than 20 particles are included as subhaloes ($1.7 \times 10^{10} \mathrm{h}^{-1} M_\odot$).

All physical processes associated to the baryonic matter are described by phenomenological prescriptions parametrized to match observed galaxy properties like luminosity and colour distributions, morphologies, gas and metal contents as explained in detail by De Lucia & Blaizot (2007; see also Croton et al. 2006). The adopted SAM models the star formation, generation of galactic winds, supernova feedback, black hole growing and also the suppression of cooling flows by AGN feedback. However, the SAM treats galaxy mergers as an instantaneous process, and does not include pre-merger star formation induced by tidal interactions. As a consequence, galaxies which are about to merge in the model (i.e. galaxy pairs) do not show any signatures of interaction in their astrophysical or morphological properties. Colours and magnitudes are estimated by adopting the population synthesis models of Bruzual and Charlot (2003), and are dust corrected following Guiderdoni & Rocca-Volmerange (1987) as explained by De Lucia & Blaizot (2007).

Thus, the synthetic galaxy catalogue (hereafter MR galaxies) provides information on star formation rates, total stellar masses (M_*), SDSS photometric magnitudes, black hole mass, masses in cold and hot gas phases, masses in metals in the different baryonic components and also dark matter halo masses.

In the SAM, galaxies are classified as: central galaxies of dark matter haloes (Type 0) or satellites (Type 1 and 2). Type 1 satellites inhabit dark matter subhaloes within larger ones while Type 2 satellites have lost their own dark matter haloes as they entered into larger ones. After losing its subhalo, positions and velocities of Type 2 satellite galaxies, are determined by those of the most bound particle of the subhalo at the last time it was identified. At this point, the satellite galaxy merges with a central galaxy after a certain merging time estimated by using the dynamical friction model (Binney & Tremaine 1987).

Thus, combining the large dark matter simulation and the SAM, it is possible to track the evolution of galaxies

Table 1. Control Samples: constraints applied to build up the analysed control samples.

Control	L	z	M_*	Σ	B/T	M_{halo}	Galaxy Type
Control 1	X	X					
Control 2		X	X				
Control 3		X	X	X			
Control 4		X	X	X	X		
Control 5		X	X	X	X	X	
Control 6		X	X	X	X		X
Control 7		X	X			X	

throughout volumes comparable to the largest current galaxies surveys such as the SDSS.

2.1 Mock galaxy pair and the basic control sample.

A reliable confrontation between observations and models requires a correct mimic of the observational procedure. We use MoMaF (Blaizot et al. 2005) to create a SDSS-DR4 mock catalogues from MR galaxies. These mocks allow us to select simulated galaxy with the same set of *observational* criteria as in Alonso et al. (2006): $0.01 < z < 0.1$ and $r < 17.77$. From this redshift and r-magnitude limited sample made of 254335 galaxies, we search for galaxy pairs imposing thresholds in projected separation ($r_{\text{p}} < 100\text{kpc}$) and relative radial velocity ($\Delta cz < 350 \text{ km s}^{-1}$) (Lambas et al 2003; Alonso et al 2004; Alonso et al 2006). We obtained a Pair Catalogue composed by 37590 galaxies. The remaining galaxies without a close companion within the adopted thresholds will constitute the Non-Pair Sample (NPS).

We calculate the local environment of galaxies by estimating the local projected density parameter defined as $\Sigma = 5/(\pi d^2)$, where d is the projected distance to the 5th nearest neighbour brighter than $\text{M}_{\text{r}} = -20.5$, with $\Delta cz < 1000 \text{ km s}^{-1}$ (Balogh et al.2004; Alonso et al.2006). The limits on redshift and r-band magnitude have been imposed over the pair and control galaxies, so that both are equally affected by incompleteness problems.

As a first order CS, we select galaxies in the NPS by requiring them to have the same redshift and absolute r-magnitude distributions than those in the Pair Catalogue. Thus, for each galaxy in a pair, we look for a NPS galaxy with the same redshift and r-magnitude but without a near companion in order to build up the first CS (hereafter, **Control 1**). In Table 1 we summarize the constraints applied to build up all the control samples discussed below.

3 ANALYSIS OF POSSIBLE BIAS EFFECTS IN THE CONTROL SAMPLE.

Taking profit of the fact that the model does not include the physics of interactions, we expect galaxies in pairs and in the CS to have the same properties, at least, if we suppose that they have experienced the same average history of assemble. So, any differences should be ascribed to bias effects in the selection of the pair sample, not to interactions. We check this hypothesis particularly focusing on the analysis of colour and cold gas distributions for galaxies in pairs

and in the CS. We use these relations because they should be strongly connected with any possible star formation activity triggered by interactions.

Comparing the colour and cold gas fraction distributions for galaxies in pairs and in the **Control 1** (Fig. 1), we can appreciate significant differences between both samples which can not be attributed to the effect of interactions as explained before. Pairs exhibit an important excess of red and a deficit of blue galaxies (and consistently, a lower cold gas fraction) compared to the **Control 1**. Other physical properties of galaxies with and without a close companion are compared, such us: halo masses (M_{halo}), local density environment (Σ), stellar masses (M_*) and bulge-to-total (B/T) ratio (Fig. 2). We find that the dark matter halo distribution (the most difficult property to measure observationally) is the one that exhibits the largest bias. In agreement with Barton et al. (2007), we find that galaxies in pairs tend to belong to larger haloes than galaxies in the **Control 1**. A less observationally demanding way to assess the role of environments in driving bias effects is by using the local projected density estimator, Σ. In agreement with previous results (e.g. Lambas et al. 2003; Alonso et al. 2004), we find that galaxy pairs tend to inhabit higher density regions that their isolated counterparts in the **Control 1**. Beside these environmental biases, the figure also shows that galaxies in pairs tend slightly to have larger stellar masses and more important bulges (i.e. larger bulge to total stellar mass, B/T) than galaxies in **Control 1**. Although, these effects are less important, we have to take them into account in order to select a suitable CS. We note however that, in hierarchical clustering scenarios, larger stellar masses systems have larger probability to have grown by mergers, which in the SAMs directly fed the bulges. So, in our samples these two parameters are very closely related.

In Fig. 3, we show number density of galaxies in pairs and in the **Control 1** on a cold gas fraction and stellar-mass weighted age (τ) plane. Galaxies in pairs tend to be $\approx 10\%$ older than those in the **Control 1**, with a mean value of τ equal to 8 Gyr h^{-1} for galaxies in pairs and 7 Gyr h^{-1} for galaxies in the **Control 1**. Consistently, galaxies in pairs have less cold gas content than galaxies in the **Control 1**. From this figure, we can also see that galaxies in pairs have clearer bimodal distributions.

A more detailed inspection of the colour and the cold gas fraction distributions for galaxies in pairs and in the **Control 1** as a function of the local density environment, reveals that the most significant difference is observed in low densities: $-2.300 < \log \Sigma < -0.285$ (Balogh et al. 2004). In such region, galaxies in pairs exhibit the largest excess of red and a deficit of blue galaxies with respect to those found in the **Control 1** (Fig. 4). Consistently, we find that in this low density, galaxies in the **Control 1** have a larger fraction of cold gas, available for the star formation activity responsible for their bluer colours. If the physics of baryons during interactions is not properly described in the SAMs, and consequently, galaxy properties only change as a result of a merger, why does the SAM predict an excess of cold gas and bluer colours for the **Control 1** respect to galaxies in pairs, particularly in low density regions.

Before analysing the other possible biases, let us take into account the different composition in galaxy types for both samples. We find that the Pair Catalogue is composed
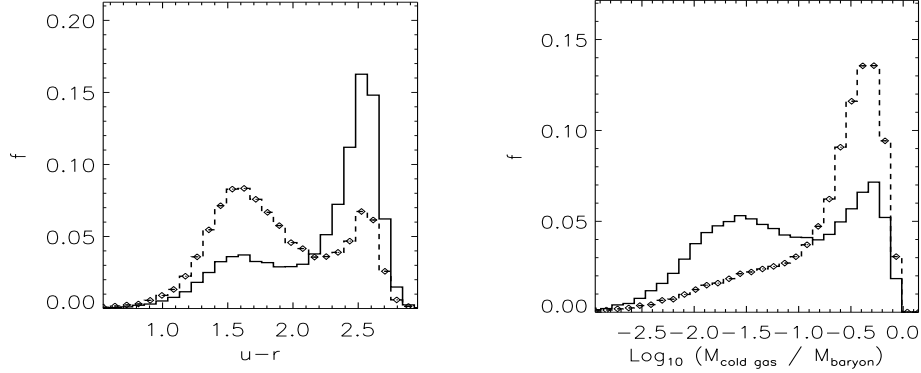
Figure 1. The (u-r) colour distributions (left panel) and cold gas fraction distributions (right panel) for both galaxies in pairs (solid line) and in the **Control 1** (dashed line). Error bars are standard deviations computed for 100 realizations of control samples (see the text for more details).
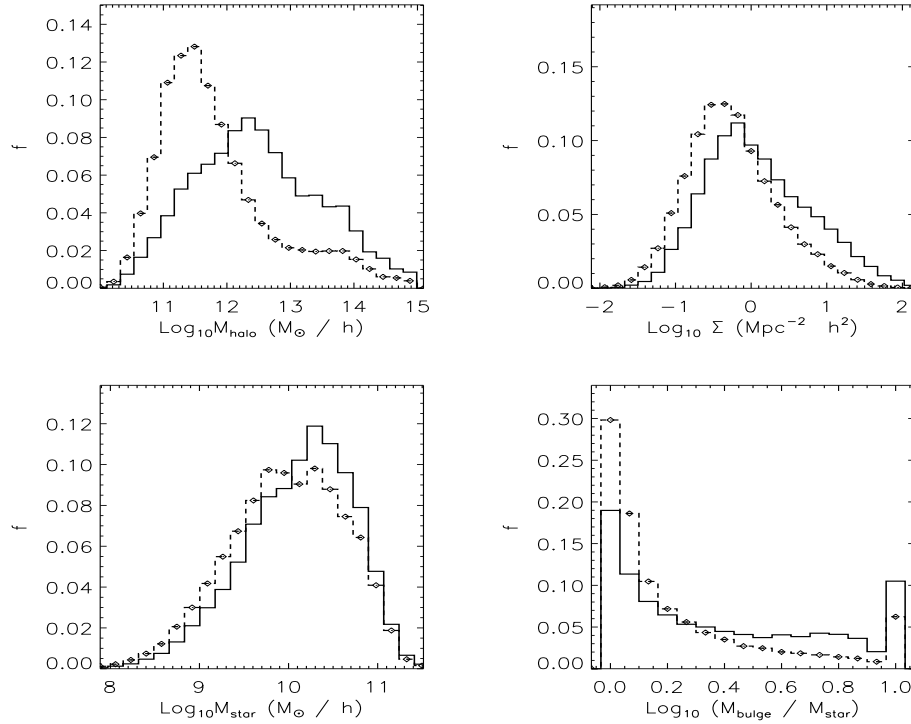

Figure 2. Histograms of the dark matter halo masses (upper left panel), local density parameter (Σ) distributions (upper right panel), stellar mass distributions (lower left panel) and, morphological distributions, represented by the bulge to total stellar masses (B/T) parameter (lower right panel), for galaxies in pairs (solid line) and in the **Control 1** (dashed line).

by a larger fraction of satellite galaxies (28% type 2 and 30% type 1) than the **Control 1** (see Table 1) which is dominated by central types ($\approx 80\%$). Central galaxies can continuously replenish their cold gas reservoir available for star formation by cooling their hot gas component. Type 2 satellites are galaxies which have lost their dark matter haloes and their hot gas components, so they do not have a source of gas accretion. Even more, Type 2 systems might have left-over cold gas but not enough to satisfy the thresh-old surface density to form stars adopted in this SAM (e.g.

Kauffmann 1996; Croton et al. 2006), and in consequence, they become passively redder and older.

The different recipes used to model both types of galaxies in the SAM are physically motivated and had been developed to mimic the effects of global environment such as strangulation. For the analysis in this current paper, it is important to bare this in mind and latter on, we will assess its effect on the results.

Concluding, we find that **Control 1**, selected at imposing only redshift and absolute r-magnitude constraints, has younger and bluer, more cold gas enriched and more
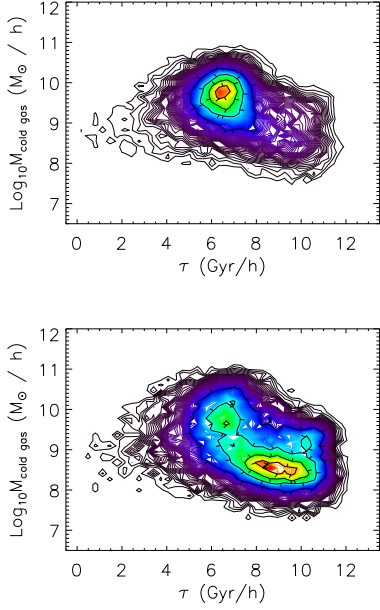
Figure 3. Contour plots of cold gas fraction and age weighted stellar mass parameter, τ, for galaxies in the **Control 1** (upper panel) and in pairs (lower panel). The sequence from red to blue colours indicates a decrease in the galaxy number density.
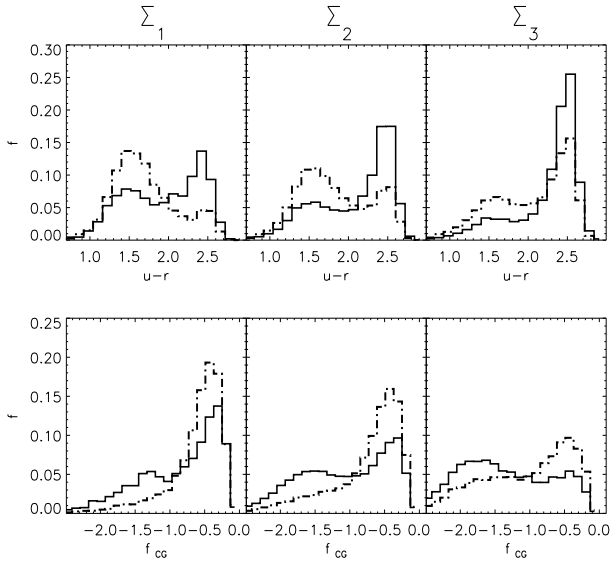

Figure 4. Histograms of colours (upper panels) and cold gas fractions, f_{CG}, (lower panels), for galaxies in the **Control 1** (dashed lines) and in pairs (solid lines). Plots have been divided in three panels corresponding to different density environments: $-2.300 < \log \Sigma_1 < -0.285$; $-0.285 < \log \Sigma_2 < 0.145$ and $0.145 < \log \Sigma_3 < 3$.

active star-forming systems than galaxies in the Pair Catalogue, biasing any direct comparison between them. The fact that, galaxies in the **Control 1** tend to inhabit lower density regions and smaller dark matter haloes contributes partially to this bias. We also find different compositions in stellar masses, types and morphologies (Fig. 2) which will be considered in the following sections.

4 ISOLATING THE INTERACTION EFFECTS.

In this Section, we systematically imposed constraints on stellar masses, local environments, morphologies and halo masses to select different control samples and compared them with the Pair Catalogue to assess the existence and importance of biases. We also established an upper limit to the importance of the galaxy type bias.

The constraints discussed in this paper can be also imposed on observed samples selected from large surveys such as 2dFGRS or SDSS where the photometry and spectroscopic of galaxies are available. However, since some of these constraints can be more difficult to impose than others, we introduced them progressively in order to individualize the effects produced by each one.

4.1 An observer's guide to unbias a control sample

It is widely accepted that stellar mass is a more fundamental quantity than luminosity (Kauffmann et al. 2003; Brinchmann et al. 2000; Baldry et al. 2006; Panter et al. 2004; Ellison et al. 2008). So, we define **Control 2** by selecting NPS galaxies which match one-to-one the redshift and stellar mass distributions of galaxies in the Pair Catalogue, (see Ellison et al. 2008, for an exhaustive discussion). As it can be seen in Fig. 5a, the colour distributions of galaxies in **Control 2** has changed favorably in comparison to that of Control 1, diminishing the differences with the colour distribution of galaxies in pairs.

We take into account the fact that galaxies in Control 1 also tend to be located in lower density regions than galaxy pairs. Hence, we define an alternative **Control 3** by selecting galaxies from the NPS with redshift, stellar mass and local density distributions matching those of galaxies in pairs. In this process, approximately 2% of the pairs samples can not be matched in the NPS, due to the under-representation of high masses and high density environments in the latter. The colour distribution of **Control 3** (Fig. 5b) shows a slight decrease and increase of the blue and the red peaks, respectively, with respect to the distribution of Control 2. Although when the agreement between **Control 3** and the Pair Catalogue is better, discrepancies are still present indicating that additional parameters, such us morphology, can be considered.

In the process of improving the definition of CS, we build the **Control 4** forcing NPS galaxies to have an additional constraint, i.e. the morphological index (B/T). In order to define this **Control 4**, almost a 6% of galaxies have been removed from the original Pair Catalogue, because they do not have a NPS counterparts which satisfies all these constraints. As shown in Fig. 5c this new CS matches better the galaxy pair colours than the previous ones.

Recently, several observational methods for estimating DM halo masses have been reported. Spitler et al. (2008) present a method to directly estimate the total mass of a dark halo using its system of globular clusters. They show that the link between globular cluster systems and halo masses is independent of a galaxy type and environment, in contrast to the relationship between galaxy halo and stellar masses. Alternatively, a group finder algorithm and a dynamical mass estimation could also be used as an observationally technique to determine halo masses. In particular, Zapata el al. (2009) use this technique to compare properties of galaxy groups in the SDSS-DR4 to those in mock catalogues. In consequence, it might be possible to build an observational CS imposing that their galaxies have the same dark matter haloes than galaxy pairs. Thus, in order to probe how further it is possible to improve the CS definition, we build the **Control 5** from NPS galaxies by imposing constraints on redshift, stellar mass, projected local density, morphology and dark matter haloes. We note that to build this CS, a considerable fraction of galaxies from the original Pair Catalogue has to be removed (approximately 40%) because of the lack of NPS galaxies inhabiting similar dark matter haloes. Fig. 5d shows that galaxies in the **Control 5** fits much more closely the colour distributions of galaxy pairs than those of previous CS. Comparing this results with the obtained by using the original **Control 1** (Fig. 1), we conclude that we find a suitable CS, feasibly defined in observational surveys.

Insets in Fig. 5 also compare the star formation activity for galaxies with and without a near companion for each CS definition. We estimated the star formation activity by defining the stellar birthrate parameter, $b = 0.5t_H(SFR/M_*)$, computed as an estimator of the present star formation rate normalized to the total stellar mass SFR/M_* (Brinchmann et al. 2004). As expected, the b distributions behave consistently with those of colours.

4.2 Additional insights from the theoretical perspective

In the previous subsection, we discuss how to build a CS applicable to real galaxy surveys, and hence, potentially used by observers. Now, we use parameters available only in simulations to go one step further analysing what we can learn from models.

An issue to be addressed is concerning the different fractions of central and satellite galaxies in each sample. As we mentioned before, in Control 1 there was an excess of central galaxy types with respect to the Pair catalogue. The analysis of galaxy type populations in **Control 5** shows a significant reduction of the fraction of central galaxies with respect to **Control 1**: from 79.8% to 57.7%. On the other hand, we have removed almost 14% of the satellite population from the original Pair Catalogue. This fact implies that by taking into account the dark matter haloes inhabited by galaxies (**Control 5**), we have also removed the bias in galaxy types. Hence both the pair sample and the **Control 5** have a final composition of $\sim 45\%$ of satellites and $\sim 55\%$ of central galaxies. Although, this final selection on halo mass is similar in spirit to the method proposed by Barton et al. (2007), our criteria is less restricted because it only requires galaxies

in pairs and in the control sample to inhabit similar mass haloes.

It turns out that most of the effect of the halo selection thus comes from getting similar proportion of central and satellite galaxies in the pair and control samples. We have checked that indeed, replacing the halo mass condition by a condition on galaxy type (central or satellite) yields similar results as Fig. 5d. We wish to note at this point that the semi-analytic model we are using tends to have too steep a behavior, in the sense that satellite galaxies redden too fast after they enter a larger halo (Wang et al. 2007). This enhances the difference between the pair and control samples unless they are built in a way which yields similar numbers of satellite and central galaxies. Hence the dis-agreement found in Fig. 5 are somewhat over-estimated. Nonetheless, this enhancement points us to a radical solution, also adopted to some extent by Barton et al. (2007), which is to match halo masses and thus remove the satellite/central issue.

In order to asses the effect of galaxy type modelling, we define **Control 6** by selecting galaxies from the NPS with similar redshift, stellar mass, local density environment, morphology type and galaxy type distributions to those of galaxies in pairs. We found that in the **Control 6**, $\approx 49\%$ and $\approx 52\%$ of the members are satellite and central galaxies, respectively. These type population frequency is very similar to that found in **Control 5** where the contrain on the dark matter halo had been imposed. However, the distribution of dark matter haloes of galaxies in pairs and in **Control 6** are still different (Fig. 6). We claim that the dark matter bias is a real effect although could be exacerbated in the SAMs so that our results should be considered upper limits (similar caution should be taken when using other models to populate haloes).

In order to quantify the performance of the building up process of a suitable control sample, we estimate the control efficiency C_e, as the ratio between the red fraction of galaxies in pairs and that of a given control sample. As shown in Fig. 7, the efficiency of the CS improves from the first Control 1 to Control 5. We can also see that Control 6 has similar C_e than Control 5. It is interesting to note how the colour distributions of pairs and controls get closer as the different biases are eliminated. In particular, 70% of the bias is already cleaned up after imposing constraints on redshift, stellar mass and local density environment to select the control sample (Control 3). Finally, just with the purpose of illustrating the importance of halo bias, we include in the figure the C_e parameter for a new **Control 7** built imposing constraints only in redshift, stellar mass and halo mass. As figure shows, although the halo mass contributes significantly to correct the total bias effect, the remainder constraints have to be considered in order to build a suitable control sample.

5 AN EXAMPLE: THE MASS-METALLICITY RELATION

The mass-metallicity relation (MZR) is a well-determined correlation between these two parameters which holds from ellipticals to dwarf galaxies (e.g. Lequeux et al. 1979; Tremonti et al. 2004; Savianne et al. 2008). Recently, many authors have studied the MZR for galaxies in pairs find-
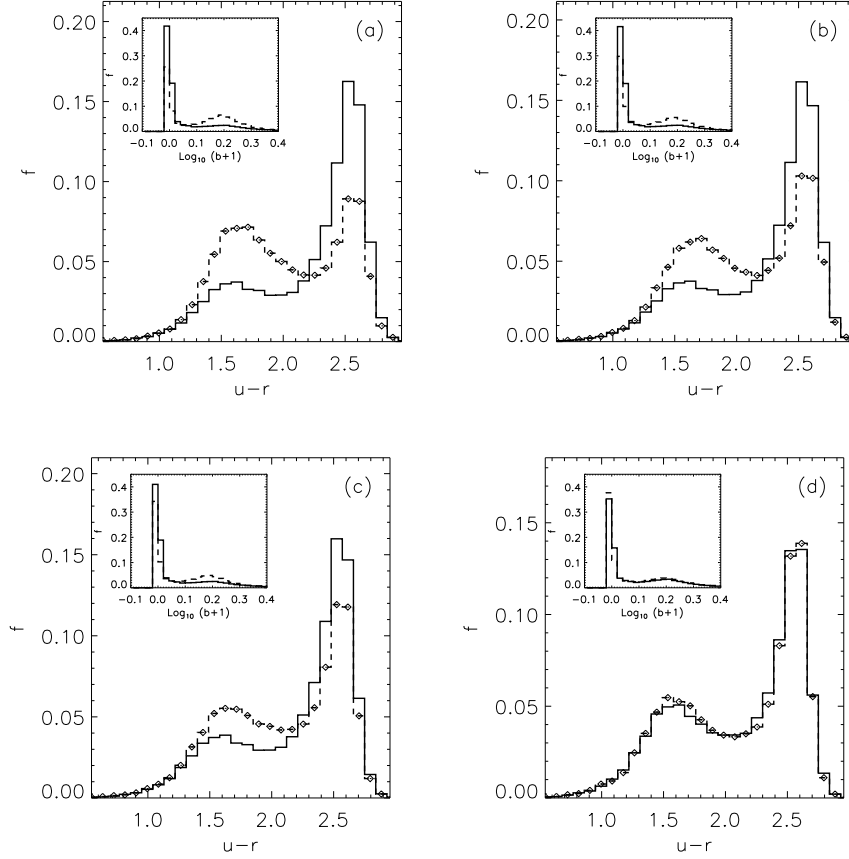
Figure 5. The u-r colour distributions for both galaxies in pairs (solid line) and without a close companion (dashed line) in **Control 2** (a), **Control 3** (b), **Control 4** (c) and in **Control 5** (d). The insets show the corresponding stellar birthrate distributions, b, for both galaxies in pairs and in control samples using the same convention of lines.
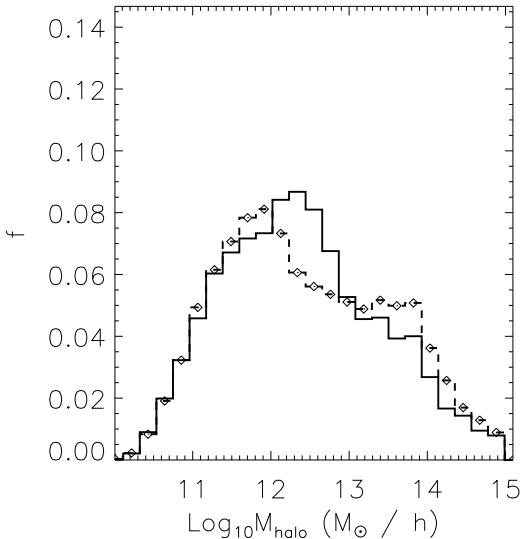

Figure 6. Dark matter halo distributions for galaxies in the Pair Catalogue (solid lines) and in **Control 6** (dashed lines).

ing that they tend to deviate from the mean MZR of their respective control samples (Kewley et al. 2006; Micheal-Dansac et al. 2008; Ellison et al. 2008).

Taking into account, the possible biases suggested by our work in the construction of control samples (see also Barton et al. 2007), we analysed their impact on the MZR of galaxies pairs in the Millennium Simulation.

We define the metallicity parameter, Z, as the mass in metals in the gas-phase component (provided by the SAM) normalized by the cold gas mass. Because this relation requires the comparison of galaxies with similar stellar components, we start from the estimation of the MZR for **Control 2** (where constraints on redshift and M_* have been applied). Nevertheless, we note that the MZR estimated from **Control 1** (which has redshift and luminosity constraints) yields similar results. As it can be seen from Fig. 8, galaxies in pairs (solid line) determine a significant different MZR compared to galaxies in **Control 2** (dashed thick line), trend which is mainly stressed for stellar masses larger than $\approx 10^{9.5} \mathrm{h}^{-1} M_\odot$. However, an important change is obtained when the environmental bias is corrected. The MZR for **Control 3** (dashed thin line) approaches that of galaxy pairs as it can be appreciated from Fig. 8. Note that this result is not modified by introducing the constraint on morphology by using the **Control 4** (not included in the figure
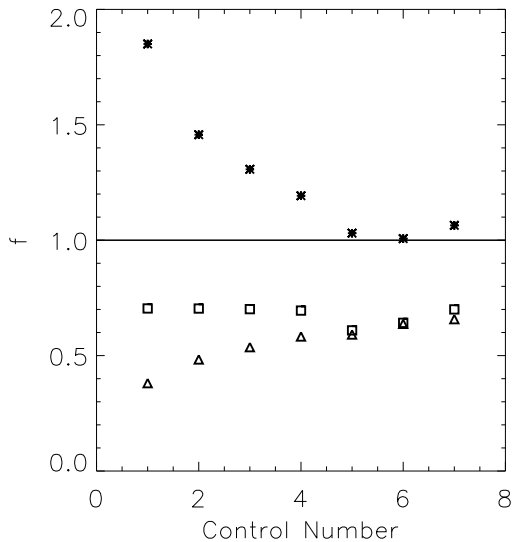
Figure 7. Control efficiency C_e (asterisk) and red fractions ($u - r > 2$, open triangles) of all analysed control samples, defined with numbers from 1 to 7 (Table 1). Red galaxy fractions computed for each corresponding galaxy pair samples are also shown (open squares). The horizontal line corresponds to have no excess of red galaxy pairs with respect to the CS.

for the sake of simplicity). Finally, we get the closest agreement between the control and pair MZRs when the halo mass bias is corrected by **Control 5** (dotted line).

For stellar masses smaller than $\approx 10^{9.5} h^{-1} M_\odot$, the MZRs for control samples always match closely that of galaxy pairs. We note that this agreement is independent of galaxy type composition which is very different between the two samples in this mass range. This suggests that the Millennium treatment of galaxy types is not important. The clue to understand this behaviour is given by the halo mass size. We find that small stellar mass systems in the control samples live preferentially in small haloes, while larger stellar systems tend to inhabit larger haloes. We estimated that 87% of **Control 2** galaxies with small stellar masses live in dark matter haloes with masses lower than $10^{12} \, h^{-1} M_\odot$, while this percentage decreases to 56% for galaxies with larger stellar masses. A similar trend is observed for galaxy pairs with a 75% and 35% of small and large stellar systems, respectively, living in small dark matter haloes. Hence, it is only at the high stellar mass end where there is a larger difference in halo composition between the control and pair samples (see Fig. 2).

These findings suggest that observational results on the MZR for galaxy pairs might be affected by biases principally at the high stellar mass end. In order to test this hypothesis, we introduce the pair metallicity excess parameter, R_Z, defined as the difference of pair and CS metallicities normalized by the pair value, and calculate it for observational and theoretical data. Fig. 9 shows the observational R_Z, computed with the O/H abundances of SDSS-DR4 galaxies generously provided by Micheal-Dansac et al. (2008) and Ellison et al. (2008) (hereafter MD08 and E08, respectively), as a function of the stellar mass. It is interesting to note that

even when they made a different selection of their pair and control samples, both trends in Fig. 9 (red and green lines) are appreciably consistent. They find that for intermediate and large stellar mass systems, the metallicities of galaxy pairs slightly tend to have lower values respect to those in their respective isolated galaxy samples. This trend reverses (at least in the case of MD08) for smaller stellar masses, with galaxy pairs showing an excess of metals respect to their isolated counterparts.

Fig. 9 also shows the pair metallicity excess of mock galaxies computed with our pair and control galaxies of Samples 2 and 5 (black and blue lines, respectively). **We warn that when comparing semi-analytical and observational R_Z values some issues must be born in mind.** First, while the O/H abundances can be estimated for SDSS galaxies, only a mean gas-phase metallicities can be obtained from the SAM. Second, because of the reduced size of the spectroscopic fiber, metallicities of SDSS galaxies tend to be nuclear (depending on the galaxy size), however, SAM provides a mean value of the global metallicity of galaxies. Finally, and probably the main reason, SAM does not include the physics of interactions, consequently, mock ZMRs certainly cannot reflect the tidal trace as in observations. **Nevertheless, these reasons do not invalidate the comparison since we are always evaluating the excess with respect to the appropriate control sample which shares the same limitations.** The inspection of R_Z for mock galaxies shows that our Samples 2 (black line of Fig. 9) exhibit a different metal content in galaxy with and without a near companion, with higher metallicities in galaxy pairs at intermediate stellar masses. However, after correcting morphology, local density environment and halo mass biases as done for Samples 5 (blue line), these differences are significantly removed. **The comparison of R_Z for Samples 2 and 5 shows that a biased selection might affect the interpretation of ZMRs only at intermediate stellar masses, suggesting that the observed values could be even lower than reported. Our results support the trends detected by MD08 and E08 at low and high stellar mass ends, where the theoretical R_Z values are almost negligibly.**

6   CONCLUSIONS.

In this work, we analyse how to build up a suitable control sample in order to isolate the effects of interactions on the colour and star formation activity distributions of galaxies in pairs. We took profit on the fact that the SAMs do not include the effects of interactions, so that, mock galaxies with and without a close companion should have similar colour distribution and star formation activity if the only difference between them is the presence of a companion.

We found that a control sample selected by imposing their members to have only the same luminosity and redshift distributions than galaxies in a pair sample ends up formed by a galaxy population that differs in gas content, stellar masses, morphology, environment and dark matter haloes. Because of these biases, galaxies in pairs seem to be artificially older, gas-poorer, bulge-dominated and tend to inhabit higher local density regions and higher DM haloes when comparing with their isolated counterparts in this ba-
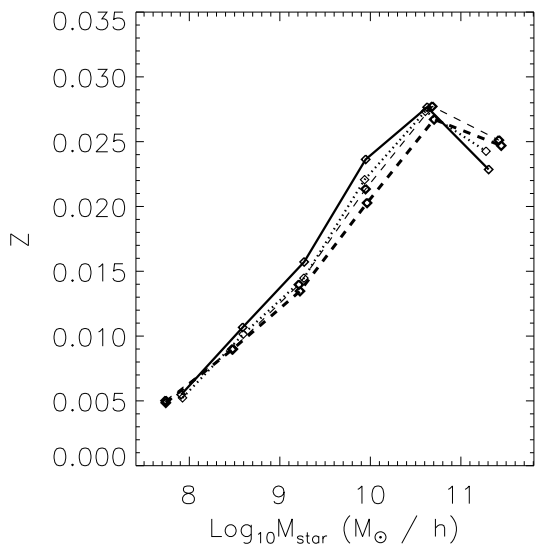
Figure 8. Mass-Metallicity relation for galaxy pairs (solid line), **Control 2** (dashed thick line), **Control 3** (dashed thin line) and **Control 5** (dotted line).
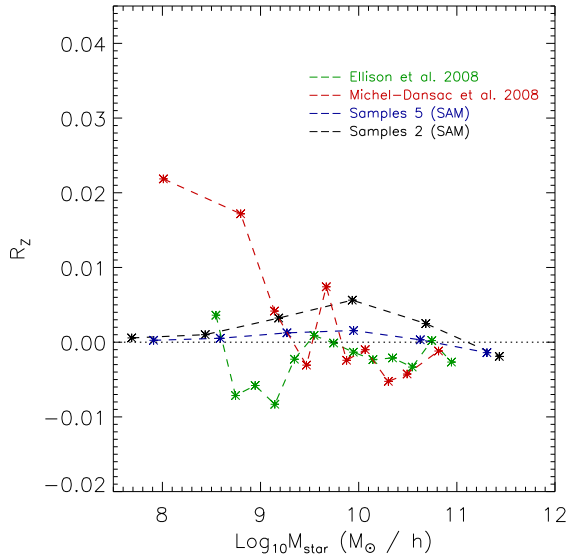

Figure 9. The pair metallicity excess, R_Z, defined as the difference between pair and CS metallicities normalized by the pair value, as a function of stellar masses. Red and green lines represent the SDSS-DR4 values computed with O/H abundances kindly provided by Michel-Dansac et al. (2008) and Ellison et al. (2008), respectively. Analogously, mock R_Z values for Samples 2 and 5 are represented by black and blue lines, respectively.

sic control sample. The galaxy pair MZR is also affected by these bias selection.

Hence, if a control sample is not cleaned from these biases, then the confrontation with galaxy pairs could yield spurious results. We systematically took each of these biases into account to correct the control samples and finally get one with the same colour distribution and star formation

activity as galaxies in pairs. This control sample also has similar gas fraction and mean stellar-mass weighted ages to those of galaxies in pairs.

We found that the differences between the control and pairs samples diminished by 70% by considering constraints on redshift, stellar mass and local density. We also showed that the effects of dark matter haloes could be overestimated in the SAM so that our estimations should be considered upper limits.

Some of the constraints we have used, such as galaxy types or halo mass, are difficult to estimate observationally. However, via the theoretical analysis of their effects we could assess how relevant they are for the study of pair galaxies. We conclude that, on one hand, galaxy type bias is the less important one compared to the environment and mass ones. On the other hand, halo mass bias could be very significant as previously reported (Barton et al 2007) but by taking into account environment bias, its effects are importantly mitigated. Our comprehensive study of mock galaxies showed that a suitable control sample for isolating the effects of interactions should be built by imposing constraints on redshift, stellar mass, local environment, morphology and halo mass. Only when these criteria are applied, the differences found in the bimodal colour distribution (MZR and star formation activity) could be directly associated to the effects of interactions.

REFERENCES

Alonso M.S., Tissera P.B., Coldwell G. & Lambas D.G, 2004, MNRAS 352, 1081
Alonso M.S., Lambas D.G, Tissera P.B.& Coldwell G., 2006, MNRAS 367, 1029
Baldry I.K., Balogh M.L., Bower R.G., Glazebrook K., Nichol R.C. et al., 2006, MNRAS 373, 469
Balogh et al, 2004, MNRAS 348, 1355.
Barnes, J. & Hernquist L., 1992, ARA&A 30, 705
Barton E.J., Geller M.J. & Kenyon S.J., 2000, ApJ, 530, 660.
Barton, E.J.; Arnold, J.A.; Zentner, A.R.; Bullock, J.S.; Wechsler, R.H., 2007, ApJ 671, 1538
Binney J., Tremaine S., 1987, Galactic Dynamics. Princeton Univ. Press, Princeton, NJ
Blaizot J., Wadadekar Y., Guiderdoni B., Colombi S.T., Bertin E. et al., 2005, MNRAS, 360, 159
Brinchmann, J.; Ellis, R.S., 2000, ApJ 536, 77
Bruzual G. & Charlot S., 2003, MNRAS 344, 1000
Colles M.M, Dalton G., Maddox S., Sutherland W., Norberg P., et al (2dFGRS Team), 2001, MNRAS, 328, 1039.

Croton D.J., Springel V., White S.D.M., De Lucia G., Frenk C.S. et al, 2006, MNRAS 365, 11

De Lucia G. and Blazoit J., 2007, MNRAS 375, 2

De Propis R. et al, 2005, AJ 130, 1516

Donzelli C.J.& Pastoriza M.G., 1997, ApJS, 111, 181

Ellison S.L.; Patton D.R.; Simard L.; McConnachie A.W.; 2008, AJ 135, 1877

Font A.S., Bower R.G., McCarthy I.G., Benson A.J. Frenk C.S. et al, 2008, (astro-ph/0807.0001)

Geller M.J., Kenyon, S.J., Barton E.J., Jarrett T.H. and Kewley L.J., 2006, AJ 132, 2243

Guiderdoni B. and Rocca-Volmerange B., 1987, A&A 186, 1

Kauffmann G., 1996, MNRAS, 281, 475

Kauffmann G., Heckman T., White S.D.M., Charot S., Tremonti C. et al, 2003, MNRAS, 341, 33

Kewley L.J. & Dopita M.A., 2002, ApJS 142, 35

Kewley L.J., Geller M.J. & Barton E.J., 2006, AJ 131, 2004

Kewley L.J. & Ellison S.L., 2008, ApJ 681, 1183

Lambas D.G, Tissera P.B., Alonso M.S. & Coldwell G. 2003, MNRAS, 346, 1189.

Larson R.B. & Tinsley B.M., 1978, ApJ, 219, 46.

Lequeux J., Peimbert M., Rayo F., Serrano A., Torres-Peimbert S., 1979, A& A, 80, 155

Lin, L.; Koo, D.C.; Weiner, B.J.; Chiueh, T.; Coil, A.L.; Lotz, J.; Conselice, C.J. et al, 2007, ApJ 660, 51

Luo, Z.; Shu, C.; Huang, J., 2007, PASJ 59, 541

Merchán, M.; Zandivarez, A., 2002, MNRAS 335, 216

Michel-Dansac, L.; Lambas D.G.; Alonso M.S.; Tissera P., 2008, MNRAS 386, 82

Mihos J.C. & Hernquist L., 1996, ApJ, 464, 641.

Nikolic B., Cullen H., Alexander P., 2004, MNRAS 355, 874.

Panter B., Heavens A.F. and Jimenez R., 2004, MNRAS 355, 764

Perez J., Tissera P.B., Lambas D.G. and Scannapieco C., 2006a, A&A 449, 23.

Perez J., Tissera P.B., Lambas D.G., Scannapieco C. and De Rossi M.E., 2006b, A&A 459, 361.

Sanders D.B. and Mirabel I.F., 1996, ARA&A 34, 749

Saviane I., Ivanov V.D., Held E.V., Alloin D., Rich R.M., et al, 2008, (astro-ph/0806.4618)

Somerville, R. S., 2001, ASPC 230, 477

Spergel D.N., Verde L., Peiris H.V., Komatsu E., Nolta M.R. et al, 2003, ApJS 148, 175

Spitler L.R. & Forbes D.A., 2008, (astro-ph/0809.5057)

Springel V., White S.D.M., Tormen G. & Kauffmann G., 2001, MNRAS 328, 726

Springel V., White S.D.M., Jenkins A., Frenk C.S., Yoshida N. et al, 2005, Nature 435, 629

Tissera P.B., 2000, ApJ, 534, 636.

Toomre, A. & Toomre, J., 1972, ApJ, 178, 623

Tremonti C.A. et al, 2004, ApJ 613, 898

Wang, L.; Li, C.; Kauffmann, G.; De Lucia, G. et al, 2007, MNRAS 377, 1419

Weinmann, S.M.; van den Bosch, F.C.; Yang X.; Mo, H.J.; Croton, D.J. et al, 2006, MNRAS 372, 1161

York, D.G., Adelman J., Anderson J.E. et al, 2000, AJ 120, 1579

Zapata T., Perez J., Padilla N. & Tissera P., 2009, MNRAS in press, (astro-ph/0804.4478)