TRACING GALAXY EVOLUTION BY THEIR PRESENT-DAY LUMINOSITY FUNCTION

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Abstract. Galaxy luminosity functions are derived for different morphological types and various colors of galaxies, to trace the evolutionary effects which a priori should be different for void and supercluster galaxies. We also analyse how the galaxy group content changes in the large-scale environment. One of the principal results is the conclusion that the evolution of spiral galaxies is almost independent of the global environment. Meanwhile, the luminosity function of elliptical galaxies depends strongly on the environment. This shows that the global environmental density is an important factor in the formation of elliptical galaxies. The results of the present study clearly show that, except the local/group environment, the global (supercluster-void) environment plays an important role in the formation and evolution of galaxies.

Key words: cosmology: observations – large-scale structure of the Universe – galaxies: luminosity function, clusters, formation

1. INTRODUCTION

One of the principal description functions for galaxies is the luminosity function (LF) that describes the average number of galaxies per unit volume as a function of galaxy luminosity. Our current understanding of the galaxy LF owes much to the 2dFGRS (Norberg et al. 2002) and SDSS surveys (Blanton et al. 2003; Montero-Dorta & Prada 2009). These new samples of galaxies make it possible to study the dependence of the LF on a large number of different galaxy properties, as galaxy morphology, colours, star formation rate, local and global density environment, etc. In this respect, the LF plays an important role in our understanding how galaxies form and evolve (see, e.g., Yang et al. 2003; Cooray & Cen 2005; van den Bosch et al. 2008).

To understand how galaxies form, we need to understand where galaxies are located; it is essential to study the dependence of the LF on the environment. It is well known from the halo occupation distribution (HOD) models that the local environment largely determines the properties of galaxies (e.g. Zandivarez et al. 2006; Park et al. 2007) : luminous galaxies tend to occupy high mass haloes and low luminosity galaxies reside mainly in low mass haloes.

The fact that the local/group environment is a dominant factor in galaxy evolution, motivates the study of the LF in galaxy groups (e.g. Colless 2004; Xia et
A likewise important, but not so well understood factor is the global environment where the galaxy is located – its place in the supercluster-void environment. In Tempel et al. (2009) we have found that the global environment has an important role in determining galaxy properties. Some studies have been dedicated only to special regions: e.g., Mercurio et al. (2006) investigates the Shapley supercluster and Hoyle et al. (2005) concentrates on the void galaxies. The dependence on the environment has been also studied numerically (Mo et al. 2004) and using semi-analytical models (Benson et al. 2003; Khochfar et al. 2007). These semi-analytical models allow us to study the influence of different physical processes on the morphological evolution, how the morphology of a galaxy changes in time.

The influence of the global environment on the LF has been investigated by Hoyle et al. (2005), using the SDSS data, and by Croton et al. (2005), using the 2dFGRS data. These results show strong environmental trends: galaxies in higher density regions tend to be redder, of earlier type, have a lower star formation rate, and are more strongly clustered. Some of these trends can be explained by the well known morphology-density relation (Einasto et al. 1974; Dressler 1980) and by the luminosity-density relation (Hamilton 1988). It is less well known how far these trends extend when moving toward extreme environments, into deep voids or superclusters.

The LF have been determined also for different morphological types of galaxies. The morphology of a given galaxy is a reflection of its initial conditions and merger history. In studies of the LF, galaxy morphology has been determined either by its colours (Yang et al. 2009), spectra (Madgwick et al. 2002; de Lapparent et al. 2003), photometric profile (Bell et al. 2003; Driver et al. 2007a) or the visual classification (Marzke et al. 1994, 1998; Kochanek et al. 2001; Cuesta-Bolao & Serna 2003; Nakamura et al. 2003). In all these studies, the classification of early-type and late-type galaxies is based on slightly different methods and/or parameters, but all studies agree that later-type galaxies have a fainter characteristic magnitude and a steeper faint-end slope of the LF. The biggest differences in previous studies are found at the faint-end of the LF, where classification is less certain than for brighter galaxies.

Additionally, recent studies have shown that dust plays an important role in galaxy evolution and it may significantly influence the luminosities and colours of galaxies (Tuffs et al. 2004; Driver et al. 2007b; Rocha et al. 2008; Tempel et al. 2010), especially for late-type galaxies. Thus, in order to study intrinsic properties of galaxies, it is necessary to take dust extinction into account. Using the SDSS data, Shao et al. (2007) and Tempel et al. (2011b) have studied the influence of dust on the LF. In general, dust is important for late-type spiral galaxies; nearly edge-on galaxies are most affected.

In this study we investigate how the large-scale environment influences the evolution of galaxies and groups. We have chosen specifically the large-scale environment, since the local/group environment has been studied exhaustively. We hope that the large-scale environment can provide a new viewing angle to understand better the evolution of galaxies. To do that, we study the LFs of galaxies for different morphological types of galaxies, and for different types of group galaxies (group brightest galaxies, satellite galaxies). In this study, we take advantage of the large spectroscopic galaxy surveys (2dFGRS and SDSS), which enable us to study the details of galaxy properties in different environments.
Fig. 1. Absolute magnitudes of galaxies in the 2dFGRS sample and in the SDSS sample at various distances from the observer. To have a better comparison between these two samples, the magnitudes of the SDSS sample were converted to the $b_J$ system.

In general, the present analysis has three goals: to determine the LFs of the group brightest (first-ranked), second-ranked, and satellite galaxies; to investigate the nature of the satellite and isolated galaxies; and, as most important, to analyse the global (large-scale) environmental dependency of galaxy luminosities for galaxies of different types and colours.

2. DATA AND METHOD OF ANALYSIS

2.1. The group catalogues

In the present analysis we shall use the flux-limited catalogues of groups and clusters for the 2dFGRS sample by Tago et al. (2006) and for the SDSS sample by Tago et al. (2008, 2010). More details of the selection effect for LF calculation are given in Tempel et al. (2009, 2011b) and Tempel (2011).

In Figure 1 the absolute magnitudes of the 2dFGRS and the SDSS samples are shown. The flux-limited selection effects are well seen: at lower distances, the brightest galaxies are absent due to the upper limiting magnitude; at further distances, only the bright galaxies are seen. While the SDSS sample includes more than three times more galaxies than the 2dFGRS sample, the 2dFGRS sample is slightly deeper than the SDSS sample.

2.2. Selection effects and luminosity function estimation

To calculate the LF of galaxies, we need to know the number of galaxies of a given luminosity bin per unit volume. The principal selection effect that influences the determination of the LFs in flux-limited surveys is the absence of galaxies fainter or brighter than the survey limiting magnitudes.

To take this effect into account in the determination of the LF, the standard $V_m^{-1}$ weighting procedure can be used. In this method the number density of galaxies can be represented by a sum of kernels centred at the data points:

$$n(L) = \sum_i \frac{1}{V_{\text{max}}(L_i)} \frac{1}{a_i} K \left( \frac{L - L_i}{a_i} \right),$$

(1)

where $V_{\text{max}}(L)$ is the maximum volume where a galaxy of a luminosity $L$ can
be observed in the present survey, and the sum is over all galaxies of the survey. The kernels $K(x)$ are distributions ($K(x) > 0$, $\int K(x) \, dx = 1$) of zero mean and of a typical width $a$. As the LF is rapidly changing with luminosity, especially at the bright end of the LF, the bin widths should vary. This is implemented by adaptive kernel estimation, where the kernel widths depend on the data, $a_i = a(L_i)$.

The kernel widths are known to depend on the density $f(x)$ itself, with $a \sim f(x)^{-1/5}$ for densities similar to normal distribution. This choice requests a pilot estimate for the density that can be found using a constant width kernel.

We are also interested in the “error bars”, pointwise confidence intervals for the number density of galaxies. These can be obtained by smoothed bootstrap. More details about the LF estimation can be found in Tempel et al. (2011b) and Tempel (2011).

2.3. Determining environmental densities

Many galaxy properties, including luminosities, depend on the environment, where the galaxy is located. We calculate the environmental densities in a similar way as done by Liivamägi et al. (2010) for supercluster search.

To calculate the luminosity density field, we need to know the expected total luminosities of groups and isolated galaxies. The primary factor that determines the calculation of group luminosities is the selection effect, present in a flux-limited survey: further away, only the brightest galaxies are seen. To take this into account, we calculated for each galaxy a distance-dependent weight factor $W_d$

$$W_d = \int_0^\infty \frac{L \, n(L) \, dL}{\int_{L_1}^{L_2} L \, n(L) \, dL},$$

where $L_1, L_2 = L_\odot 10^{0.4(M_\odot - M_1, 2)}$ are the luminosity limits of the observational window at distance $d$, corresponding to the absolute magnitude limits of the window $M_1$ and $M_2$, and $n(L)$ is the LF for all galaxies. To calculate the magnitudes $M_1$ and $M_2$ we use the average $k + e$-corrections at a given distance.

Assuming that every galaxy also represents a related group of galaxies, which may lie outside the observational window of the survey, the estimated total luminosity per one visible galaxy is

$$L_{\text{tot}} = L_{\text{obs}} \cdot W_d,$$

where $L_{\text{obs}}$ is the observed luminosity of the galaxy. The luminosity $L_{\text{tot}}$ takes into account the luminosities of unobserved galaxies and therefore it can be used to calculate the full luminosity density field.

The left panel of Figure 2 shows the weight factor $W_d$ for the 2dFGRS and SDSS samples. The right panel of Figure 2 shows the average global densities in thin concentric shells as a function of distance for the SDSS sample. The global density is nearly constant over the distance, when the weight factor is applied. Variations in average density are due to the large-scale structure.

In the present study we shall divide all galaxies into four classes, according to the value of the global environmental density $D$ at their location. The highest density class represents the supercluster region, the lowest class is the void region, and the two intermediate classes are between these two classes. We designate these
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2.4. Accounting for dust attenuation in spiral galaxies

Recent studies have shown that dust plays an important role in galaxy evolution and it may significantly influence the luminosities and colours of galaxies (Tuffs et al. 2004; Driver et al. 2007b; Rocha et al. 2008; Tempel et al. 2010), especially for late-type galaxies. Thus, in order to study intrinsic properties of galaxies, it is necessary to take dust extinction into account.

Spiral galaxies have more dust than ellipticals and therefore the observed luminosities of spiral galaxies are more affected by dust. If we want to correct for dust attenuation, we have to know the morphology of a galaxy.

In our classification for the SDSS sample about half of the galaxies (45%) are spirals, about one quarter (25%) are ellipticals and for 30% of galaxies, the classification is unclear.

For the studies of LF in SDSS samples, we have corrected the galaxy luminosities for internal dust attenuation. The details of the dust attenuation calculation are given in Tempel et al. (2010, 2011a). The galaxy classification and application for the SDSS galaxies are described in Tempel et al. (2011b) and Tempel (2011).

3. RESULTS

Figure 3 shows the LFs in different environments: from voids (D1) to superclusters (D4). In each panel the attenuation-corrected LFs are shown. The most notable trend is that while moving from lower global densities toward higher ones, elliptical galaxies start to dominate the bright end of the LF. In the least dense environments, ellipticals and spirals are equally abundant at the bright end of the LF (spirals even slightly dominate at the bright end in the void environment); in the densest environments, the brightest galaxies are mostly ellipticals. At the faint end of the LF, while moving from low density regions to high density regions, the difference between ellipticals and spirals decreases; in denser environments, the fraction of elliptical galaxies increases.

In Figure 4 the LFs for red and blue spiral and elliptical galaxies are shown for different environments. For elliptical galaxies, the bright end of the LF moves...
toward higher luminosities when moving toward higher environmental densities. This means that bright elliptical galaxies are residing mostly in high density environments, e.g., in the cores of galaxy clusters, which are more prominent in superclusters than in voids.

Interestingly, the LF for spiral galaxies is almost independent of environment. The bright end of the LF for the least dense environment is also slightly different from that for other environments, because generally, very bright galaxies are absent from low density environments (Tempel et al. 2009).

Figure 4 shows that, in general, the faint end of the LF is mostly built up by bluer galaxies and the bright end includes mostly redder galaxies; this behaviour is the same for spirals and ellipticals. In Figure 4 we also see that the increase of the number of bright ellipticals in dense environments is mostly caused by red ellipticals.

In Figure 5 we show the LFs for group galaxies. Each panel represents a different environment, and in each panel we show the LFs of different populations (the first-ranked, second-ranked, satellite, and isolated galaxies).

Figure 5 (upper-left panel) shows that in voids, the bright end of the LFs of all galaxy populations is shifted toward lower luminosities. Interestingly, the bright end of the LF for isolated galaxies in voids is comparable to that of the first-
Fig. 4. Attenuation-corrected LFs for red (upper panels) and blue (lower panels) populations; for spirals (left panels) and ellipticals (right panels), in different global environments. The shaded areas show the 95% confidence regions of the LFs.

ranked galaxies. This suggests that the isolated galaxies are actually brightest galaxies in groups, where the group fainter members are unobserved due to the faint magnitude-limit of the survey.

The LFs for the supercluster (D4) environment are shown in Figure 5, lower-right panel. We notice the striking difference between the LFs in superclusters and the LFs in other environments: here all LFs have a well-seen decrease at the faint end of the LF, which for the first-ranked galaxies was seen already in the D3 environment.

When comparing the first-ranked and isolated galaxies, the LFs in the void (D1) environment are quite similar. In the void environment, the differences between the first-ranked and isolated galaxies are the smallest: i.e., in the void environment the first-ranked galaxies of groups are fainter than those in higher density environments. When moving toward higher densities, the differences between these two populations increase: the bright end of the LF of the first-ranked galaxies becomes more luminous and at the faint end, isolated galaxies start to dominate.

Furthermore, at the faint end of the LF, in the void environment, the differences between these four populations are quite small. When moving toward higher global environments, the differences at the faint end of the LF are increasing. This suggests that in the void environment, the formation of faint galaxies is similar for all populations. In the void environment, mergers are not the dominant factor in galaxy evolution and quiescent evolution can form galaxies of all types in a quite similar way.
In summary, the most dense environment (superclusters) is different from other environments: the numbers of faint galaxies decrease while moving toward yet fainter galaxies, and the brightest first-ranked galaxies are brighter than the first-ranked galaxies in lower density environments (compared with other populations).

4. CONCLUSIONS

In the present study the 2dFGRS and the SDSS were used to study the LF of galaxies for different samples in various global environments. The global luminosity density field was used to define the large-scale environments with different global densities from voids to supercluster cores. We used the 2dFGRS sample to derive the LF of group galaxies: for the brightest (first-ranked), second-ranked, satellite, and isolated galaxies. We also studied the nature of isolated galaxies, and demonstrated that isolated galaxies are not truly isolated at all. We used the SDSS data to construct the LFs separately for galaxies of different morphology (spiral and elliptical) and of different colours. For the SDSS sample, we took special care to correct the galaxy luminosities for the intrinsic attenuation, since for spiral galaxies the attenuation can affect significantly the galaxy luminosity.

The principal results of the present study are the following:

1. The LF of elliptical galaxies depends strongly on the environment, and the environment is more important for red elliptical galaxies than for blue elliptical galaxies. This suggests that global environmental density is an important...
2. The evolution of spiral galaxies (the LF of spiral galaxies) is almost independent of the global environment, especially for blue and red spirals separately, showing that spiral galaxy formation has to be similar regardless of the surrounding global density.

3. The highest global density regions (superclusters) are significantly different from other regions. Here the fraction of elliptical galaxies is greater than in other environments and there are relatively less faint spiral galaxies than in the low-density counterparts.

4. The brightest galaxies are absent from the void regions. After correcting for the intrinsic absorption, spiral galaxies dominate the LF of void regions at every luminosity. In higher-density environments, the faint end of the LF is determined by spiral galaxies and the bright end by elliptical galaxies. For all environments, the faint end includes mostly blue galaxies and the bright end mostly red galaxies.

A comparison of these results with predictions of numerical simulations and/or semi-analytical models would provide stringent constraints on the driving factors of the formation and evolution of galaxies in dark matter haloes. These results show clearly, that beside the local/group environment, also the global (supercluster-void) environment plays an important role in the formation and evolution of galaxies. Finally, to understand the complex processes that lead to the formation of present-day galaxies, we cannot ignore the location in the large-scale environment, where the galaxy resides. Hopefully, accounting for the role of global environment can help to solve some of the unsolved problems in a general picture of galaxy formation and evolution.

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