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Securing the Faint End of the Galaxy Luminosity Function

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Abstract: The history of the formation of galaxies must leave an imprint in the properties of the mass function of collapsed objects and in its observational manifestation, the galaxy luminosity function. At present the faint end of the luminosity function is poorly known. Accurate knowledge of the luminosity function over the full range of galaxy clustering scales would provide serious constraints on both initial cosmological conditions and modulating astrophysical processes.

Wide field imaging surveys with large ground-based telescopes now provide the capability to identify dwarf galaxy candidates to very faint levels ($\mu_R \approx 26$ mag arcsec^{-2}), too low in surface brightness for spectroscopy (measuring redshifts) even with telescopes like Keck. Other means have to be explored to get distance information for these candidates in order to separate cluster members from back/foreground systems beyond doubt. On the quest to establish the properties (slope and possible turning point) of the the faint end of the galaxy luminosity function we are employing the surface brightness fluctuation (SBF) method to determine adequate distances, potentially resulting in the best definition ever of the luminosity function to $M_R \approx -11$ in the cluster and group environments.

Keywords: galaxies: distances and redshifts — galaxies: dwarf — galaxies: luminosity function — galaxies: mass function

1 The Constituents of the Luminosity Function

Thompson & Gregory (1980) and Kraan-Korteweg (1981) were the first to explore the luminosity functions (LFs) of individual galaxy types, followed by the comprehensive surveys of the clusters in Virgo (Binggeli et al. 1985), Fornax (Ferguson 1989), and Centaurus (Jerjen & Tammann 1997). The latter three surveys were probing the LFs down to low luminosities ($M_B \sim -13$) and surface brightnesses ($\mu_B \approx 25$ mag arcsec^{-2}). Based on these highly complete (as later demonstrated by Drinkwater et al. 1999), volume-limited galaxy samples it was shown that the LFs of the three classical Hubble types are bound at the bright *and* at the faint end. More quantitatively, the comparative study by Jerjen & Tammann (1997) found evidence that the LFs of giant ellipticals, lenticulars, and spirals are analytically well described by Gaussian functions while only the LFs of the two dwarf families (ellipticals and irregulars) steadily increase to very low luminosities and follow Schechter (1976) functions with faint end slopes $\alpha \leq -1$ beyond all detection limits to date.

Combining the findings from the type-specific LFs with either the morphology–density relation for giants (Dressler 1980) and dwarfs (Binggeli et al. 1990) or the dwarf-to-giant ratio variation as a function of environment can naturally explain the diversity of overall luminosity functions that have been observed in clusters, groups, and the field (Jerjen et al. 1992). Plateaus and dips in the giant/dwarf transition region at $M_R \approx -19$ are particularly difficult to describe with a simple Schechter function. This prompted more recent studies to adopt a two-component Gauss+Schechter (giants+dwarfs) analytic expression instead (e.g. Trentham & Tully 2002).

2 Theory versus Observations

It is becoming increasingly evident that there are fewer dwarf galaxies per giant galaxy observed than anticipated by the popular Cold Dark Matter (CDM) hierarchical clustering paradigm and the proposition of a constant relationship between baryons and dark matter in diverse environments (Klypin et al. 1999; Moore et al. 1999; Trentham & Tully 2002). Is there a problem with the cosmological paradigm or with the baryon to dark matter proposition? Variations on CDM cosmology, such as Warm Dark Matter (Bode et al. 2001) or Self-Interacting Dark Matter (Spergel & Steinhardt 2000) would be reflected in variations in the bottom end of the mass spectrum of collapsed structures. Alternatively, there is no shortage of astrophysical mechanisms that can diminish the accumulation of baryons in low mass potential wells: long cooling times for primordial gas in small halos (Haiman et al. 1996); galactic winds driven by supernovae and hot stars (Dekel & Silk 1986); pressure support

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against collapse of the intergalactic plasma after reionisation (Thoul & Weinberg 1996; Gnedin 2000). Recipes that include these astrophysical processes in semi-analytic models (Blanton et al. 1999; Somerville et al. 2001; Ostriker et al. 2003) produce turn downs in the mass function of cluster/group halos below $10^{12} M_{\odot}$. A cutoff of this nature is reported in observations (Tully 2003).

The present situation is confused because there are a multitude of reasons the faint end of the luminosity function could deviate from the simple CDM theory expectation and a dearth of observational constraints. The various mechanisms are expected to generate distinctive features either directly in the mass spectrum (the mechanisms with cosmological origins) or only in the resultant luminosity function (due to cutoffs in the influences of the astrophysical mechanisms). It has been pointed out (Tully et al. 2002) that the mechanism related to reionisation could be expected to generate an environmental dependency that seems to be observed. The hierarchical merging process happens earlier, at a more rapid pace, in places that ultimately become rich clusters compared with lower density regions. Consequently a larger fraction of dwarf galaxies have formed before reionisation in higher density places. These early-forming dwarf halos collect cold gas, the ingredient of star formation. Dwarf halos forming later, after reionisation, are unable to pull in the hot gas that now surrounds them. This scenario can explain the apparent observation that low density regions have fewer dwarfs per giant than high density regions.

Progress on this important problem is currently limited by observations, not theory. This is shown by the inconsistent results for instance for the Virgo cluster where a steep faint end slope of $\alpha = -2.0$ is claimed by Phillipps et al. (1998) which stands in contrast to Trentham & Hodgkin (2002) who found over no magnitude range the slope to be steeper than $\alpha = -1.6$. Another example is the Fornax cluster. Kambas et al. (2000) reported $\alpha = -2.0$ for their galaxy sample while Hilker et al. (2003) subsequently identified most of the galaxies as background objects revising the slope to $\alpha = -1.1 \pm 0.1$. Last but not least, there are the significantly different results from the Sloan Digital Sky Survey ($\alpha = -1.05 \pm 0.01$; Blanton et al. 2003) and the 2dF Galaxy Redshift Survey ($\alpha = -1.21 \pm 0.03$; Norberg et al. 2002). We must conclude from these results that despite the enormous effort that has been put into LF studies *we presently lack detailed information on the luminosity function in the range of extreme dwarfs in any environment*. Whether there are variations with environment is very uncertain.

3 Finding Extreme Dwarfs

The most important ingredient to probe the galaxy luminosity function to faintest luminosities and surface brightnesses is our ability to inventory large swaths of sky with wide field CCD imagers. In our on-going program to secure the faint end galaxy luminosity function in the local Universe, we use MegaCam at the 3.6-m CFHT for wide field coverage and SuprimeCam at the 8-m Subaru Telescope for deep penetration of selected fields. We are working with the hypothesis that the luminosity function of galaxies may vary with environment (Binggeli et al. 1988; Jerjen & Tammann 1997; Tully et al. 2002) so our program involves surveys of a variety of environments. We want to go to the faintest possible levels so the regions being studied are the nearest possible representative locations. Presently, imaging data has been obtained for our program in eight separate galaxy groups within the domain of the Local Supercluster, ranging from the dense and rich Virgo Cluster, through dense but sparse, and low density but rich, to low density and sparse. Early results from the program have been published (Trentham, Tully, & Verheijen 2001; Trentham & Tully 2002). The imaging program comfortably identify dwarf candidates as faint as $M_R = -11$, and pushes as faint as $M_R = -8$ with the Subaru material in selected locations.

Trentham & Tully (2002) introduced a rating scheme that describes prospective group members (probable, possible, plausible, implausible). From our present experience upon the collection of redshifts and from consideration of spatial correlations, it appears that a very high percentage of targets rated probable or possible are, in fact, members. Moreover, roughly half of 'plausible' candidates might well be members. Very few of the candidates called 'implausible' are expected to be members. However, this issue of group membership versus chance projection has to be carefully tested as it is the outstanding problem with regard to the establishment of the properties of the faint end of the luminosity function.

4 Distances Based on Surface Brightness Fluctuations

According to our present understanding, the vast majority of dwarf galaxies can be distinguished by their low surface brightness properties. There is a hedge here because it is known that high surface brightness dwarfs do exist (Drinkwater et al. 2003). High surface brightness objects are accessible to spectroscopic studies, so their status as potential group members can be evaluated by their correlation in redshift. Such objects only make minor contributions to the luminosity function in studies to date. The focus of our study is on low surface brightness objects. Neutral hydrogen detection provides confirmation in a fraction of cases, as high as 30% in a low density group at 20 Mpc. Optical spectroscopy can provide redshift information and positive group identifications for high to moderate surface brightness objects. However, the very lowest surface brightness galaxies are inaccessible to spectroscopy even with the largest telescopes.

The alternative way to establish group memberships is through distance determinations based on the surface brightness fluctuation (SBF) method (Tonry & Schneider 1988). In the case of the SBF method, the tip of the red giant branch is unresolved but the statistical fluctuations in the distribution of Red Giant Branch stars can be recorded

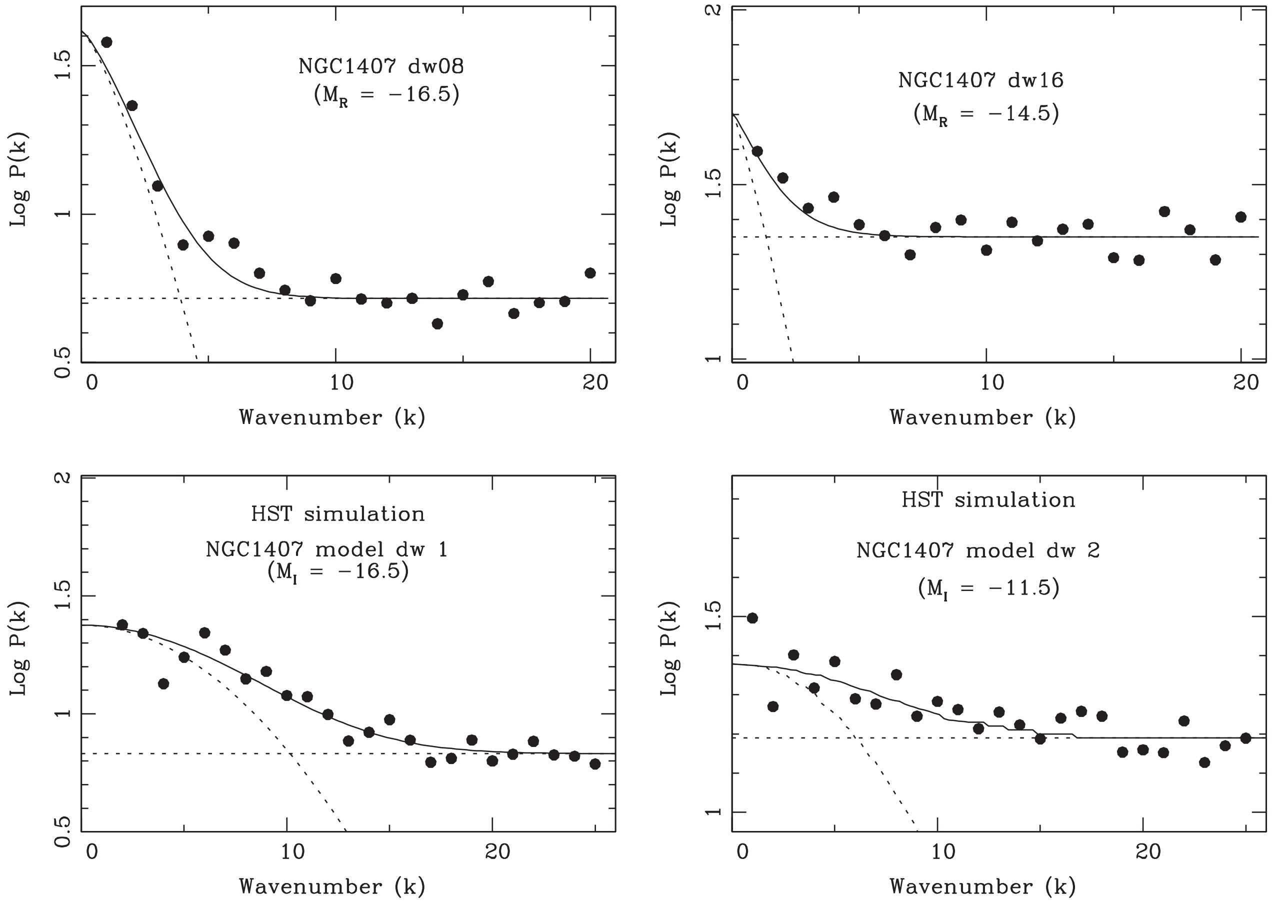

Figure 1 The top two panels show examples of R-band power spectra of NGC 1407 Group galaxies obtained with 12 min exposures in $1''$ seeing with the 8-m Subaru Telescope. The bottom two panels show simulated I-band power spectra of targets at the NGC 1407 distance of 25 Mpc as would be obtained with 20 min exposures with HST/ACS. The absolute magnitudes of the targets are indicated in the panels. The brighter and fainter simulated targets have central surface brightnesses of 22.5 and 25 mag arcsec^{-2} respectively. The observations and simulations (filled circles) are well fitted by the sum (solid line) of a scaled version of the power spectrum of the point spread function and a constant (dashed lines). We note that $R - I$ is generally small ($\approx$0.5) for early-type dwarfs and thus the results from the two filters comparable.

and the power spectrum of these fluctuations provides an accurate estimate of distance. The efficacy of this method is well demonstrated when applied to E/S0 high surface brightness systems (Tonry et al. 2001). This methodology has now been demonstrated to work equally well with low surface brightness spheroidal systems within the 10 Mpc sphere (Jerjen et al. 1998, 2000, 2001). Applying the method to the brightest of dwarfs ($-15 > M_V > -18$), relative distances are determined at the level of 9% rms accuracy at the distance of the Virgo and Fornax clusters (17–20 Mpc) using images obtained with the 8-m VLT in good seeing (Jerjen 2003; Jerjen et al. 2004).

First tests with our Subaru and CFHT images showed that they provide SBF signals satisfactory for distance estimates for galaxies in the NGC 1407 Group at 25 Mpc. The NGC 1407 Group is quite noteworthy. Dense knots of early type galaxies are found across a considerable scale range from rich clusters with in excess of $10^{15} M_\odot$ to just a few big galaxies in a halo of $10^{13} M_\odot$ (Tully 2003). Within the domain $V < 3000$ km s^{-1}, the NGC 1407 Group is the best case at the low mass end of this range of E/S0 knots. It contains only two L* galaxies, yet the one-dimensional velocity dispersion is 385 km s^{-1} (comparable to the Fornax Cluster). It contains many dE dwarfs. The first goal of our program is to measure as many SBF distances of the 232 group member candidates as possible.

Examples of the SBF signal due to the stellar component of two dwarf galaxies in this group are seen in the top panels of Figure 1. In fitting the power spectrum, data at low frequencies ($k < 5$) should be ignored because these frequencies are affected by imperfect galaxy model subtractions. It can be seen that the target of the top left panel, NGC 1407 dw08, has an adequate power spectrum signal for an SBF measurement. However, the power spectrum for the two magnitudes fainter NGC 1407 dw16 (top right panel) is quite inadequate, particularly given the fact that the first four points on the left ($1 < k < 4$) should not be considered. It is evident that we are approaching the practical limit of ground-based observations at 25 Mpc already at $M_R \sim -15$. The exposure times of the ground-based observations could be increased by a factor of ten (two hours) and with better seeing, $M_R \sim -14$ is probably attainable from the ground. Power spectrum signals for faint dw16-like dEs would then be observed as strong as the one shown for dw08 in Figure 1. However, reaching fainter, low-surface brightness dEs from the ground appears highly impractical as similar quality data would require total integration times in excess of ten hours.

Of the 232 NGC 1407 group member candidates, 63 are brighter than $M_R \sim -14$, hence, accessible to a ground-based SBF study. It is a sample of ~50 of the 169 candidates *fainter* than this limit that shall be observed in single orbit SNAP mode with the Hubble Space Telescope in Cycle 14. Such shallow images provide sufficient signal to determine a distance to members of the group for even the faintest of our targets. The top and bottom panels of Figure 1 explore the faintward limits obtainable with ground-based and HST/ACS observations, respectively. The tremendous advantage of HST due to exceptional seeing and absence of sky background is apparent. As discussed, the power spectrum seen in the upper right of a $M_R = -14.5$ galaxy observed with Subaru is not adequate. By contrast, the power spectrum seen in the lower right of the simulated dwarf with $M_I = -11.5$ is entirely adequate due to a broader power spectrum of the stellar PSF and the low shot noise level (dashed lines). The signal remains above the noise out to $k \sim 15$. Indeed, the SBF detection with HST/ACS of a dwarf with $M_I = -11.5$ will be better than the SBF detection with the current Subaru data of the galaxy with $M_R = -16.5$. We will comfortably be able to measure SBF signals for our faintest candidates.

5 Summary

Most recent studies of the galaxy luminosity function showed that the ambiguity in attributing membership status to cluster/group galaxy candiates is still the main source of uncertainty on the quest to find the accurate shape, slope, and possible turning point of the faint end of the galaxy luminosity function, i.e. the *dwarf* galaxy luminosity function. Various observational and analysis techniques used to date lead to quite different and inconsistent results for the same galaxy environment signalling that the faint end of the luminosity function is in fact only poorly known at present.

To achieve an accurate separation between group members and background/foreground objects we are currently exploring the possibility to verify membership of large numbers of weakly luminous, low surface brightness group candidates by means of measuring SBF distances using high quality wide-field imager data and HST images. First tests for dwarf galaxies as faint as $M_I = -11.5$ in the NGC 1407 group at 25 Mpc are very promising. Results from our extensive SBF analysis of early-type dwarfs along the line-of-sight of this group will be combined with spectroscopic and neutral hydrogen data for the other group member candidates to calibrate the membership rating scheme as employed by Trentham & Tully (2002) so that the luminosity functions found in the studied eight galaxy environments will be better constrained, permitting progress on the important question of whether there are genuine differences with environment.

References

Binggeli, B., Sandage, A., & Tammann, G. A. 1985, AJ, 90, 1681
Binggeli, B., Sandage, A., & Tammann, G. A. 1988, ARA&A, 26, 509
Binggeli, B., Tarenghi, M., & Sandage, A. 1990, A&A, 228, 42
Blanton, M., Cen, R., Ostriker, J. P., & Strauss, M. A. 1999, ApJ, 522, 590
Blanton, M., et al. 2003, ApJ, 592, 819
Bode, P., Ostriker, J. P., & Turok, M. 2001, ApJ, 556, 93
Dekel, A., & Silk, J. 1986, ApJ, 303, 39
Dressler, A. 1980, ApJ, 236, 351
Drinkwater, M., et al. 1999, ApJ, 511, L97
Drinkwater, M., et al. 2003, Natur, 423, 519
Ferguson, H. C. 1989, AJ, 98, 367
Gnedin, N. Y. 2000, ApJ, 542, 535
Haiman, Z., Thoul, A. A., & Loeb, A. 1996, ApJ, 464, 523
Hilker, M., Mieske, S., & Infante, L. 2003, A&A, 397, L9
Jerjen, H. 2003, A&A, 398, 63
Jerjen, H., Binggeli, B., & Barazza, F. D. 2004, AJ, 127, 771
Jerjen, H., Freeman, K. C., & Binggeli, B. 1998, AJ, 116, 2873
Jerjen, H., Freeman, K. C., & Binggeli, B. 2000, AJ, 119, 166
Jerjen, H., Tammann, G. A., & Binggeli, B. 1992, in Morphological and Physical Classification of Galaxies, eds. G. Longo et al. (Kluwer: Eindhoven), p. 17
Jerjen, H., & Tammann, G. A. 1997, A&A, 321, 713
Jerjen, H., et al. 2001, A&A, 380, 90
Kambas, A., et al. 2000, AJ, 120, 1316
Kraan-Korteweg, R. C. 1981, A&A, 104, 280
Klypin, A., Kratsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Moore, B., et al. 1999, ApJ, 524, L19
Norberg, P., et al. 2002, MNRAS, 336, 907
Ostriker, J. P., Nagamine, K., Cen, R., & Fukugita, F. 2003, ApJ, 597, 1
Phillipps, S., Parker, Q. A., Schwartzenberg, J. M., & Jones, J. B. 1998, ApJ, 493, L59
Schechter, P. 1976, ApJ, 203, 297
Somerville, R. S., et al. 2001, MNRAS, 320, 289
Spergel, D. N., & Steinhardt, P. J. 2000, PhRvL, 84, 3760
Thompson, L. A., & Gregory, S. A. 1980, ApJ, 242, 1
Thoul, A. A., & Weinberg, D. H. 1996, ApJ, 465, 608
Tonry, J., & Schneider, D. P. 1988, AJ, 96, 807
Tonry, J., et al. 2001, ApJ, 546, 681
Trentham, N., & Hodgkins, S. 2002, MNRAS, 333, 423
Trentham, N., & Tully, R. B. 2002, MNRAS, 335, 712
Trentham, N., Tully, B. R., & Verheijen, M. A. W. 2001, MNRAS, 325, 385
Tully, R. B. 2003 (astro-ph/0312441)
Tully, R. B., Somerville, R. S., Trentham, N., & Verheijen, M. A. W. 2002, ApJ, 569, 573