THE FAINT END OF THE LUMINOSITY FUNCTION IN THE FIELD

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Abstract

I review the current observational status of the faint end of the optical luminosity function of field galaxies at low redshift. There is growing evidence for an excess number of dwarf galaxies that is not well fit by a single Schechter function. These dwarf galaxies tend to be of late morphological and spectral type, blue in colour, of low surface brightness and currently undergoing significant star formation.

1 Introduction

The galaxy luminosity function (LF) characterizes the number density of galaxies as a function of luminosity, or absolute magnitude. The faint end of the LF tells us the abundance of dwarf galaxies, accurate knowledge of which is important for constraining models of both galaxy formation and evolution.

Most local galaxy surveys (e.g. [4, 6, 10, 15, 17]) have found a value of $\alpha$ that lies in the range $-1.2 \lesssim \alpha \lesssim -0.7$, giving a “flat” faint-end slope when the LF is plotted as a function of absolute magnitude. However, there is recent evidence that the faint end of the LF is not well fit by a Schechter function:

$$\phi(L)dL = \phi^* \left(\frac{L}{L^*}\right)^\alpha \exp\left(-\frac{L}{L^*}\right) d\left(\frac{L}{L^*}\right).$$
1. An analysis of the CfA redshift survey by Marzke et al. [15] finds that although the best-fit Schechter function has \( \alpha = -1.0 \pm 0.2 \), there is a significant excess of galaxies above the Schechter fit at magnitudes \( M_Z \gtrsim -16 \).

2. For the Las Campanas Redshift Survey, Lin et al. [6] measure a faint-end slope of \( \alpha = -0.70 \pm 0.05 \) in the Gunn-\( r \) band. However, all of their data points fainter than \( M_r \approx -17.5 \) lie above this Schechter fit.

3. In their analysis of the ESO Slice Project (ESP) redshift survey, Zucca et al. [22] find that the \( b_J \) luminosity function is best fit by a flat faint-end Schechter function for \( M_{b_J} < -17 \) and a power-law of slope \(-1.57\) at fainter magnitudes.

Given the importance of the number-density of local dwarf galaxies for theories of galaxy formation and evolution, it is extremely desirable to better constrain the faint-end of the luminosity function. The problem is that most galaxies in flux-limited surveys have \( L \sim L^* \) and measuring galaxy redshifts to fainter magnitudes does not increase the number of dwarf galaxies relative to the number of bright galaxies. There is no substitute for surveying large numbers of faint galaxies to constrain the faint-end of the LF. Thus we require either to carry out large redshift surveys, such as 2dF [3] and SDSS [7], or to estimate galaxy redshifts from their photometric colours or clustering properties.

In the following section I will describe how one can constrain the space density of dwarf galaxies from counts of faint galaxies around bright galaxies of known redshift. I will then review the properties of galaxies which dominate the faint-end of the LF and discuss future prospects for measuring the field galaxy LF.

## 2 Constraining the Space Density of Dwarf Galaxies

If one has a large, photometric galaxy sample, and redshifts for a subset of these galaxies, one can make use of the fact that excess galaxies seen close in projection to galaxies of known redshift are likely to be at the same distance. This is a statistical generalization of the method used to determine the luminosity function of galaxies in clusters in which one assumes that all galaxies in a cluster are at the same distance from the observer. Due to the large numbers of galaxies, one can estimate \( \phi(M) \) to faint luminosities [16, 8].

### 2.1 Method

Consider in turn each redshift survey (centre) galaxy at distance \( y_i \):

- Count galaxies in bins of projected separation \( \sigma = y_i \theta \) (where \( \theta \) is the angular separation) and apparent magnitude \( m \) about each centre.

- The excess counts above a random distribution gives an estimate of the product \( X(\sigma, M) = \Xi(\sigma) \times \phi(M) \), where \( \Xi(\sigma) \) is the projection of the spatial correlation function \( \xi(r) \) along the line of sight:

\[
\Xi(\sigma) = \int_{-\infty}^{+\infty} \xi(\sqrt{\Delta y^2 + \sigma^2}) d\Delta y.
\]

One then averages \( X(\sigma, M) \) over all centre galaxies with minimum-variance weighting and divides \( X(\sigma, M) \) by an assumed \( \Xi(\sigma) \) to obtain a final estimate of \( \phi(M) \).

1Throughout, absolute magnitudes will be quoted assuming a Hubble constant \( H_0 \) of 100 km s\(^{-1}\) Mpc\(^{-1}\)
2.2 Results

The above analysis was carried out using 2.4 million APM galaxies and 1787 centre galaxies from the Stromlo-APM redshift survey \cite{8}. The estimated LF is shown in Figure 1, where we have counted faint galaxies to a projected separation $\sigma \leq 1h^{-1}\text{Mpc}$ and we have assumed that the galaxy correlation function is given by the power-law $\xi(r) = (r/5.1h^{-1}\text{Mpc})^{-1.71}$. We see two major differences from a flat faint-end Schechter function:

1. The estimated LF drops below a flat faint-end Schechter function in the luminosity range $-17 \leq M_{bj} \leq -14$. This is most likely due to the fact that this analysis assumes galaxies cluster independently of their luminosity, whereas we know that sub-$L^*$ galaxies are more weakly clustered than $\sim L^*$ galaxies \cite{9}.

2. Faintward of $M \approx -15$, the LF steepens and exceeds a flat faint-end Schechter function by $M = -14$.

To model the observed $\phi(M)$, we have fitted a modified form of the Schechter function, with an additional faint-end power law:

$$
\phi(L) = \phi^* \left( \frac{L}{L^*} \right)^{\alpha} \exp \left( \frac{-L}{L^*} \right) \left[ 1 + \left( \frac{L}{L_t} \right)^{\beta} \right].
$$

In this formulation $\phi^*$, $L^*$ and $\alpha$ are the standard Schechter parameters, $L_t$ is a transition luminosity between the two power-laws and $(\alpha + \beta)$ is the power-law slope of the very faint-end. No physical interpretation is intended by this choice of formula, it is merely a convenient way of modeling the observed $\phi(L)$ over this extended range of luminosity and for estimating the faint-end slope. The line in Figure 1 shows the best-fit “double power-law” luminosity function, which has parameters: $\alpha = -0.94$, $M^* = -19.65$, $\phi^* = 0.0154h^{-3}\text{Mpc}^3$, $M_t = -14.07$ and $\beta = -1.82$ (not $\beta = -2.82$ as erroneously stated in \cite{3}). Although this fit is poor over the
range $-17 \lesssim M \lesssim -14$, our $\phi(M)$ estimate is almost certainly biased low over this range by the weaker clustering of galaxies fainter than $L^*$. Clearly, the faint-end slope $\alpha + \beta \approx -2.8$ cannot extend to indefinitely low luminosities, but it shows no obvious signs of flattening brightward of $M = -12$.

Since we are essentially measuring the product of the galaxy luminosity function $\phi(M)$ with the projected correlation function $\Xi(\sigma)$, then any dependence of $\Xi(\sigma)$ on galaxy luminosity can bias our estimate of $\phi(M)$. Thus the faint-end turn up could be due to a genuine increase in the local density of dwarf galaxies or an artifact caused by strong clustering of dwarf galaxies around $L^*$ galaxies.

However, one can place a lower limit on the space density of dwarf galaxies by making the extreme assumption that they only exist close to $\sim L^*$ galaxies. We see an excess of dwarf galaxies up to a projected separation of at least $5h^{-1}\text{Mpc}$ from $\sim L^*$ galaxies [8]. Thus a limit may be estimated by assuming that they occur with the measured space density only within $5h^{-1}\text{Mpc}$ of an $\sim L^*$ galaxy. Integrating [8] over the magnitude range $-15 \leq M_{b_j} \leq -12$, we measure a space density $\bar{n} \approx 0.20h^3\text{Mpc}^{-3}$. A lower limit on the average mean density of dwarf galaxies is then given by multiplying this by the fraction of space within $5h^{-1}\text{Mpc}$ of an $\sim L^*$ galaxy ($\approx 0.6$). We thus arrive at a limit on the space density of dwarf galaxies, here defined to lie in the luminosity range $-15 \leq M_{b_j} \leq -12$, of $\bar{n} \geq 0.12h^3\text{Mpc}^{-3}$. This is a factor of two higher than the density $\bar{n} \approx 0.058h^3\text{Mpc}^{-3}$ inferred from the extrapolation of a $\alpha = -1.11$ Schechter function [10].

In fact, the true space density of dwarf galaxies is likely to be significantly higher than this, for a number of reasons. First, our estimator assumes that galaxy clustering is independent of luminosity, whereas we know that sub-$L^*$ ($-19 < M < -15$) galaxies are less strongly clustered than more luminous galaxies [4]. If this luminosity segregation extends to dwarf ($M > -15$) galaxies, then we will have underestimated their space density. Second, analysis of simulations [8] shows that our estimator tends to underestimate the faint-end slope of $\phi(M)$ slightly, possibly due to a Malmquist-type bias. Third, as discussed by numerous authors (eg. [20] and references therein), most galaxy surveys are likely to be missing a substantial fraction of low surface brightness galaxies, many of which will be dwarfs. For example, Sprayberry et al. [20] find a pronounced upturn in the luminosity function for their sample of low surface-brightness galaxies. Thus the true space density of dwarf galaxies in the magnitude range $-15 \leq M_{b_j} \leq -12$ could be significantly higher than $\bar{n} = 0.12h^3\text{Mpc}^{-3}$.

A high space density of dwarf galaxies, assuming that they are predominantly late-type, blue galaxies (see following section), which suffer smaller $K$-correction dimming than redder, early-type galaxies, helps provide a natural explanation for the steep observed number counts of faint galaxies. Gronwall and Koo [5] were able to match observations of galaxy number counts in the $K$, $R$ and $B_J$ bands, as well as colour and redshift distributions, for a mild evolution model by assuming that the faint end of the galaxy luminosity function is dominated by blue galaxies ($B - V \leq 0.6$), and rises significantly above a Schechter function with flat faint-end slope. The Gronwall & Koo model total luminosity function is plotted in Figure [4], and one sees remarkably good agreement with our observations. These results thus support the argument of Gronwall & Koo; there is no need to invoke exotic forms of galaxy evolution to explain observed galaxy number counts at faint magnitudes.

As a final caveat, I would stress that all existing data on the LF of galaxies fainter than $M \approx -15$ comes from galaxies within a distance of $115h^{-1}\text{Mpc}$ (within $30h^{-1}\text{Mpc}$ for $M \geq -12$) and so the estimated faint-end LF is susceptible to sampling fluctuations. More data is certainly needed before we can really claim to have nailed down the faint end of the galaxy luminosity function.
3 Properties of Dwarf Galaxies in the Field

In this section I review measurements of the luminosity function of galaxy samples selected by morphological and spectral type, colour, surface brightness and star-formation activity to investigate the properties of galaxies that dominate the faint-end of the LF. The faint-end slope $\alpha$ in what follows refers to a standard Schechter function fit performed by the respective authors.

Morphology Marzke et al. [14] have measured the luminosity function of galaxies in the CfA redshift surveys selected by morphological type. They find that the LF of galaxies with Hubble types ranging from E to Sd all have a flat faint-end slope, but that the LF of Magellanic spirals and irregulars has faint-end slope $\alpha = -1.87$. Very similar results are found from a recent analysis of the Southern Sky Redshift Survey (SSRS, [13]), in which the LF of irregular/peculiar galaxies has faint-end slope $\alpha = -1.81 \pm 0.24$.

Spectral Type Bromley et al. [2] have classified galaxies in the Las Campanas Redshift Survey by spectral type. The faint-end slope $\alpha$ is seen to steepen systematically and significantly from earliest ($0.54 \pm 0.14$) to latest ($-1.84 \pm 0.11$) spectral classification. These authors also find that the faint-end slope steepens with local density for early type-galaxies; for late-type galaxies there is no significant luminosity-density relation. A steepening of faint-end slope with later spectral types is also seen in a preliminary analysis of data from the 2dF Redshift Survey [3].

Colour Marzke & da Costa [12] have subdivided the SSRS into blue and red samples at $(B-R) = 1.3$. The blue sample is well-fitted by a Schechter function with faint-end slope $\alpha = -1.51 \pm 0.18$; the red sample with $\alpha = -0.67 \pm 0.24$.

Surface Brightness Sprayberry et al. [20] have measured the luminosity function from an APM survey of low surface brightness (LSB) galaxies. Fitting a Schechter function to their LF they measure $\alpha = -1.42$. However, their data is better fit by a Schechter function with $\alpha = -0.92$ for galaxies brighter than $M_B = -16$ and a power law with slope $-2.20$ for fainter galaxies. They find that the space density of LSBs exceeds that of “normal” high surface-brightness galaxies for $M_B \geq -15$.

Star Formation Activity Several authors have recently measured the LF of galaxies selected by star-formation activity. Lin et al. [6] subdivided the Las Campanas Redshift Survey into two using the equivalent width of the $[O_{II}] 3727$ line and found that star-forming galaxies ($W_\lambda > 5\AA$) have $\alpha = -0.9 \pm 0.1$ versus $\alpha = -0.3 \pm 0.1$ for non star-forming galaxies. The later spectral types of [2] also correspond to strong emission-line galaxies. Similarly, Zucca et al. [22] find a significantly steeper faint-end slope for galaxies with detected $[O_{II}]$ in the ESP survey. We [11] have recently measured the LF of galaxies in the Stromlo-APM survey selected by equivalent width of both H$\alpha$ and $[O_{II}]$ lines. The LFs for the H$\alpha$ selected samples are shown in Figure 4; we see very similar results for the $[O_{II}]$ selected samples. We find that galaxies with significant star-formation dominate the luminosity function fainter than $M_{hJ} \approx -19$.

It is thus apparent that the faint-end of the field galaxy luminosity function is dominated by galaxies which tend to be of late morphological and spectral type, blue in colour, of low surface-brightness and which are currently undergoing significant star-formation. These results strongly suggest that it is dwarf irregular galaxies, rather than dwarf ellipticals, that dominate the faint end of the luminosity function in the field. This contrasts with dwarf galaxies in cluster environments, which are mostly dwarf ellipticals (Trentham, these proceedings).
Figure 2: Estimates of the luminosity function for galaxies in the Stromlo-APM survey with no significant detected H\(\alpha\) emission (\(W_\lambda H\alpha < 2 \text{\AA}\): circles, solid line), with moderate H\(\alpha\) emission (\(2 \text{\AA} \leq W_\lambda H\alpha < 15 \text{\AA}\): squares, dashed line) and with strong H\(\alpha\) emission (\(W_\lambda H\alpha \geq 15 \text{\AA}\): triangles, dot-dashed line). For clarity, data points representing fewer than five galaxies have been omitted from the plot. The inset shows 1 \& 2\(\sigma\) likelihood contours for the best-fit Schechter parameters.

4 Future Prospects

In the near future, two large new redshifts surveys will have a dramatic impact on measurement of the field LF. The Anglo-Australian Telescope 2dF Galaxy Redshift Survey [3] will measure redshifts for \(\sim 250,000\) galaxies to \(b_J = 19.5\) and for \(100,000\) galaxies to \(R = 21\). The Sloan Digital Sky Survey (SDSS [7]) will image \(\pi\) sr of the northern sky in 5 colours to \(r' \approx 23\) and measure redshifts for \(10^6\) galaxies. I have made five simulations of the SDSS main galaxy spectroscopic sample (900,000 galaxies to \(r' = 18\)) assuming a Schechter LF with \(\alpha = -1.0\) and \(M^* = -19.5\). The LF for each simulation was estimated using the stepwise maximum likelihood estimator [4] and in Figure 3 I show the mean estimated LF along with the rms dispersion between the simulations. One can see that we can expect to measure a reliable LF to \(M_{lim} \approx M^* + 7.5\), or even fainter if the LF does indeed have a steeper faint-end slope.

One would expect to be able to determine the LF to \(\approx M^* + 11\) by measuring the clustering of faint galaxies in the SDSS about galaxies with measured redshifts. The large SDSS dataset and accurate photometry will enable the clustering of galaxies as a function of luminosity as well as separation \(\xi(r, L_1, L_2)\) to be accurately determined. Thus the uncertainty in the luminosity-dependence of the correlation function, which dominates the errors in constraining the space density of dwarf galaxies described in §2, will be avoided.

Photometric redshifts estimated from the five SDSS colours (eg. [21]) will be extremely important for studying evolution of the LF, but of limited use for the local faint-end since the uncertainty in photometric redshift \(\delta z_{\text{phot}} \approx 0.03\). Possibly the best determination of the faint-end of the field galaxy LF will come from spectroscopic followup of faint \(z_{\text{phot}} < 0.1\) galaxies selected from the SDSS.

As emphasized elsewhere [1, 2], galaxies of different morphological or spectral type have different luminosity functions, and the LF for each galaxy type should be measured independently. The Sloan Digital Sky Survey will provide a wealth of morphological, colour and spectral infor-
Figure 3: Simulated LF we expect to measure from the Sloan Digital Sky Survey spectroscopic galaxy sample assuming that the true LF is given by a Schechter function with $\alpha = -1.0$, $M^* = -19.5$ (smooth curve). Note that we will be able to reliably measure the LF to 7.5 magnitudes fainter than $M^*$.

information for each galaxy and thus enable a careful study of the dependence of the LF on galaxy properties.

The simulated LF in Figure 3 assumes that the SDSS galaxy sample will be purely flux-limited. In practice of course, surface brightness also plays an important role in galaxy detection. For example, Sprayberry et al. [20] argue that most existing local galaxy catalogues have missed a substantial fraction of (LSB) galaxies. Since the SDSS imaging will be carried out in drift-scan mode, detection of LSB objects will be limited by photon statistics rather than flat-fielding errors. We expect to be able to detect at $5\sigma$ a $r' = 19.5$ galaxy with a scale-length of $16''$ and a central surface brightness of $27.5$ mag arcsec$^{-2}$ [19]. Even though we will not be able (or even attempt) to measure redshifts for most galaxies of this surface brightness, the surface brightness selection criteria will be very well defined and therefore correctable.

5 Conclusions

1. Evidence is building that a single Schechter function cannot fit the observed LF over a wide range of magnitudes. This is at least partly due to the fact that galaxies of different morphological type have differing LFs.

2. Several surveys are finding excess galaxies above a Schechter function at the faint end.

3. These excess galaxies tend to be of late morphological and spectral type, blue in colour, of low surface-brightness and undergoing significant star-formation. The faint-end of the field LF is thus dominated by dwarf irregular rather than dwarf elliptical galaxies.

4. A turnup in the LF of dwarf galaxies can help reconcile faint galaxy number counts and redshift distributions without the need to invoke exotic evolutionary models.
5. Future surveys, such as The Sloan Digital Sky Survey (SDSS), will enable us to measure
the field galaxy LF to \( M \approx M^* + 11 \), provided proper account is taken of surface brightness
selection effects.

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