Density-Dependent Luminosity Functions for Galaxies in the Las Campanas Redshift Survey

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ABSTRACT

Galaxies in the Las Campanas Redshift Survey are classified according to their spectra, and the resulting spectral types are analyzed to determine if local environment affects their properties. We find that the luminosity function of early-type objects varies as a function of local density. Our results suggest that early-type galaxies (presumably ellipticals and S0’s) are, on average, fainter when they are located in high-density regions of the Universe. The same effect may operate for some, but not all, late-type galaxies. We discuss the implications of this result for theories of galaxy formation and evolution.

Subject headings: galaxies: luminosity function — surveys — cosmology: observations — cosmology: large-scale structure of the universe

1 Introduction

As a snap-shot of a dynamic, evolving system, the present-day distribution of galaxies offers strong constraints for theories of structure formation. One of the best established of these, the density-morphology relation (Dressler [1980]), quantifies the extent to which the mix of galaxy types is dependent on the local environment. It is likely that the principal process responsible for this relation is the merging of galaxy pairs: Elliptical galaxies lie preferentially in high-density regions because, there, they had access to an abundant supply of objects with which to merge.

Any galaxy-formation scenario must also account for the observations of galaxies at earlier epochs (e.g., Ellis [1988]). For example, a population of late-type galaxies observed at $z \approx 1$ has no apparent counterpart among galaxies seen in the present epoch (Broadhurst, Ellis & Shanks et al. [1988]). Conversely, some early-type (S0) objects are relatively abundant at present, but similar objects, or even obvious progenitors, are less prevalent at a redshift near unity (Dressler et al. [1997]). It may not be simple to connect galaxies of the distant past and those of the present epoch with a consistent model of cosmic structure formation.

The purpose of this note is to report an effect which adds to the growing list of requirements for a successful theory of galaxy formation. Specifically, in a study of a population of galaxies in the present epoch, we find that the luminosity function of some galaxy types depends on local density: Early-type galaxies tend to be fainter when they are located in dense environments. This result is based on an analysis of galaxies in the Las Campanas Redshift Survey (Shectman et al. [1996]), the parameters of which are briefly outlined here in §2. We use a spectral classification scheme and a simple partition of galaxies into low- and high-density subsamples to evaluate the environmental dependence of type-specific luminosity functions; details and specific results are given in §3. We finish this note with possible interpretations of our results (§4).
2 The Redshift Data

The Las Campanas Redshift Survey consists of approximately 26,000 galaxies selected in the R-band, as described by Shectman et al. (1996). The survey volume consists of six narrow strips in the plane of the sky, three in the northern Galactic hemisphere and three in the south, which an effective depth of roughly 30,000 km/s. The selection of galaxies is somewhat detailed, with apparent magnitude limits, central surface brightness cuts, and sampling rates that vary across the sky. All of the selection parameters have been quantified and are incorporated into the analysis performed here following the prescription given by Lin et al. (1996). As in the previous work, when estimating luminosity functions we limit ourselves to regions of the sky which were sampled at with a 112-fiber spectrometer and which have the largest sampling rates and least stringent central surface brightness cuts.

Here we identify galaxy types using the spectral classification scheme described by Bromley et al. (1998). Types come from a principal component analysis of rest-frame galaxy spectra and are distinguished largely by the degree of line emission superimposed on a spectrum typical of a red stellar population. We consider the same six types defined in the earlier paper, labeled $C = 1, 2, ..., 6$; $C = 1$ objects have spectra with no emission-line features, while $C = 6$ galaxies show very strong emission. The correlation between the spectral types and morphology is expected to strong (e.g., Kennicutt 1992) and the nomenclature of “early” (connoting ellipticals and S0’s) and “late” (connoting spirals) are applied to low and high $C$ values, respectively.

3 Luminosity Functions by Type and Density

Our central result is a variation in the luminosity distribution of some galaxy types with environment. The analysis is essentially statistical; we consider only the distribution of luminosity among galaxies of a given type. Here luminosity functions are estimated in two ways, following Lin et al. (1996). The first is the non-parametric estimator proposed by Efstathiou, Ellis & Peterson (1988) to obtain the unconstrained form of the luminosity functions. The second is a fit to a Schechter function,

$$\Phi(M) = A 10^{+0.4(\alpha+1)(M_r - M^*)} \exp(-10^{0.4(M_r - M)})$$

where $\alpha$ and $M^*$ correspond to the slope of the faint-end of the galaxy distribution and to a typical absolute magnitude, respectively, and $A$ is a normalization constant. To obtain both types of estimators, we use a maximum likelihood method (Sandage, Tammann & Yahil 1978). In the case of the Schechter parameterization, we limit the range in absolute R-band magnitude to $-23 < M_r < -17.5$, as in Lin et al. (1996).

We must also devise a way for determining the local density of a galaxy so that the survey can be partitioned into high and low density regions. For this purpose a friend-of-friends algorithm (Huchra & Geller 1982) is sufficient, as the objective here is to simply and unambiguously determine high density regions above some threshold. An advantage of this method is that prominent redshift-space distortions in virialized clusters are handled quite well. A disadvantage is that the method is susceptible to misclassification of galaxies in small groups. Here we choose link parameters of 75 km/s in the plane of the sky and 500 km/s along the line of sight. The resulting grouped galaxies, tagged as “high-density”, with a 4-object minimum group size, constitute about one-third of the total survey. A crude estimate of the density threshold is approximately 1,000 times the mean. Galaxies observed with the 50-fiber spectrometer were included in the group-finding step so that dense structures can span the gaps in the survey which may exist between the 112-fiber fields.

Figure 1 illustrates the dependence of the type-dependent luminosity functions on density while Figure 2 gives the best-fit Schechter parameters. The early-type galaxies ($C = 1, 2, 3$), accounting
for over 70% of the objects in the survey, show significant variation: the faint-end slope steepens with density, with $\alpha$ shifting by about $-0.5$. From the best-fit values of the Schechter parameters, we calculate that the mean luminosity of early-type galaxies in high-density regions is approximately 50–80% less than in the low-density regions. The late-type objects show little or no significant trend.

We must be wary that this result may reflect some property of the survey other than true environmental dependence of type-specific luminosity functions. A flag for this cautionary statement is the discrepancy in the type-independent luminosity functions obtained in the northern and southern subsamples. Lin et al. (1996) found that the faint-end slopes from the Schechter parameterization in these two regions differ by 0.1 ($\alpha_N = -0.75 \pm 0.04$ and $\alpha_S = -0.65 \pm 0.04$). Lin et al. argue that the mismatch is probably not entirely at the faint end, but represents some broader differences in the luminosity function over the whole range of magnitudes under consideration.

Unfortunately, a north-south discrepancy persists in the type-specific luminosity functions, although to a somewhat lesser degree. It is statistically significant (above the 2-$\sigma$ level) only for types 1 and 3. Nonetheless, our result concerning the change of faint-end slope with environment can be seen in the northern and southern subsamples separately, and at about the same strength in terms of changes in the faint-end slope.

We note that the type-independent luminosity functions of the high- and low-density subsamples also exhibit differences in their faint-end slopes. Compared to the full catalog, with $\alpha = -0.70 \pm 0.03$, we find values of $\alpha_h = -0.80 \pm 0.05$ and $\alpha_l = -0.65 \pm 0.05$ for high- and low-density objects respectively. The fact that the effect is weaker in the type-independent analysis is partially a reflection of the density-morphology relation—earlier types are brighter on average than late types and are relatively more numerous in high-density regions.

Other possible concerns include aperture effects from the finite size of the spectrometer fibers (3.5" in diameter). These could alter the type assignment of galaxies in a redshift-dependent way if the spectrum from the central region of a galaxy differs significantly from that of the galaxy as a whole. Presumably this would affect late-type objects the most, since they may have localized regions of star formation. One way to test for such a “bias” is to partition the survey into high- and low-redshift subsamples and estimate luminosity functions. Taking a threshold redshift of $cz = 30,000$ km/s, we find that there is a trend for faint-end slopes to be steeper (more negative) in the high-$z$ subsample, but that the difference is statistically significant for only one type ($C = 4$). Furthermore, within these subsamples, the environmental dependence of $\alpha$ is observed, although it is stronger in the low-$z$ galaxies.

We now consider the implications of these results for the overall luminosity distribution of galaxies in the LCRS. As recommended by Binggeli, Sandage & Tammann (1988), we may write the general luminosity function of the full catalog as

$$
\Phi_g(M) = \sum_{c=1}^{6} f_c \Phi_c(M),
$$

where $\Phi_c$ is the luminosity function for type $c$, and $f_c$ is the relative abundance of galaxies of this type in a given region of the universe. This will be spatially varying as a result of the density-morphology relation. The steepening of the luminosity function with increasing density occurs simultaneously with the density-morphology effect (see Table 1 of Bromley et al. 1998). We can take both effects into account, writing a more general form than in equation (2), call it the grand luminosity function,

$$
\Phi_G(M) = \sum_{c,d} f_{cd} \Phi_{cd}(M),
$$

where the fraction of galaxies $f$ and the type-dependent luminosity functions both acquire a density index (here $d$ is a 1-bit number). An estimate of this function from the LCRS data shows that it
is not significantly different from the general luminosity function defined in equation (2). Thus for the purposes of understanding the global properties of a catalog, the general luminosity function is a reasonable approximation, as suggested by Binggeli et al. (1988).

4 Discussion

The density dependence of the faint-end slope of the type-specific luminosity functions, call it the $\alpha$-density relation, suggests that on average galaxies of a given type are fainter in dense regions than in the field. This behavior is qualitatively consistent with the observation that the dwarf-to-giant ratio of early-type galaxies is higher in groups than in the field (Ferguson & Sandage 1991). However, from a theoretical standpoint, this is perhaps an unexpected result. Press-Schechter theory predicts a relative decrease in low-mass objects in overdense regions, as a result of a steeper decline of power with scale. One might assume that this prediction applies to galaxies of a single type and therein lies the unexpectedness of the $\alpha$-density relation.

It may be that the Press-Schechter prediction is more suggestive of the change in the mix of galaxy types with density as opposed to the dependence of intrinsic properties of any one galaxy type. Thus, to understand any sort of $\alpha$-density relation, one may have to identify the processes which determine a galaxy’s type. Whatever these processes, the LCRS data suggest that they allow galaxies of a specific type to end up with less mass in dense regions than in the field. Toy models which show this behavior may be easy to construct, but it may be more challenging to identify such an effect in more developed theories of structure formation or numerical simulations.

Without subscribing to specific toy models, we note a few processes which might affect the dependence of type-specific luminosity functions. The most promising is tidal stripping of an evolved galaxy or its progenitors in high-density regions. This would cause faint galaxies to become fainter, and bright galaxies to become brighter, assuming that the stripped material is transferred from one galaxy to another. There is a hint that this might be occurring: $M_*$ shifts slightly toward the bright end for galaxies in high-density regions. Alternatively, the gaseous component of the stripped material may be lost to the intergalactic or intracluster medium, and hence would not strongly affect the bright population of galaxies.

Another possible process that could affect the $\alpha$-density relation is quenching of star formation in high-density regions. If one were to move a late-type galaxy from the field to a compact group or cluster, it is possible that a hot intergalactic (or intracluster) medium would produce sufficient $X$-radiation to reduce the star formation rate in the galaxy. This would cause the galaxy to be “misclassified” as an earlier type in our spectral scheme. Such a type migration would, to a crude approximation, steepen the faint-end slope of an early-type population simply by mixing early- and late-type luminosity functions.

One must be careful in associating the environmental dependence of the luminosity function with changes in the brightness of individual galaxies as predicted, for example, in the tidal stripping scenario. In particular, making individual galaxies fainter does not necessarily cause the slope of the luminosity function to rise toward the faint end. If the faint-end slope is steep to begin with, and if tidal stripping effects become more important with decreasing luminosity, then the faint-end slope could actually decrease, at least when measured over a finite range of luminosity. This might be a partial explanation for the fact that two of the late-type luminosity functions do not show a significant change in $\alpha$.

While the effect we have identified in the LCRS data may be a useful constraint for theories of galaxy formation in its own right, we are missing a possibly crucial body of information, namely a list of galaxy morphologies. The evidence is that morphology and spectral type are strongly correlated, but not perfectly so (Kennicutt 1992; Connolly et al. 1993; Zaritsky, Zabludoff & Willick 1995).
Differences in this correlation from high- to low-density regions might help to distinguish between the various scenarios that could produce the environmental effect reported here.

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Fig. 1.—The luminosity function by type and density. Nonparametric fits are shown for objects in high-density regions (dark triangles) and low-density regions (open circles). The labels indicate type index; the pair of curves at the bottom were produced by merging samples of the three late-type objects. The excess numbers of faint, early-type galaxies in the high-density cases are evident from the relative flatness of the luminosity functions above a magnitude of −20. The effect is not significant for the combined late-type galaxies.
Fig. 2.—Error ellipsoids for the best-fit Schechter parameters for objects in high and low density regions. The ellipsoids show 95% confidence intervals for objects found in high-density regions (solid contours) and low-density regions (dashed contours). The labels indicate type index, the × symbols mark best-fit values for the subsamples, and the solid circles indicate best-fit density-independent values. There is a significant shift in both $M_*$ and $\alpha$ for some objects, particular those of type 2, as a result of local density. The downward translation of $\alpha$ values indicates a relative excess in the number of faint galaxies in the high-density cases.