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DOI: 10.1888/0333750888/2604

Luminosity Function of Galaxies

Helmut Jerjen

From

Encyclopedia of Astronomy & Astrophysics

P. Murdin

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ISBN: 0333750888

Institute of Physics Publishing
Bristol and Philadelphia

Downloaded on Thu Mar 02 23:30:35 GMT 2006 [131.215.103.76]

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Luminosity Function of Galaxies

The definition of the (optical) luminosity function (LF) of galaxies follows those of other astronomical objects such as stars or globular clusters. It is the number of galaxies that exist in a given volume of space having a given luminosity. Thereby, 'luminosity' generally means a total magnitude in any photometric passband U, B, V, R, I, etc. However, because of the spectral sensitivity of photographic plates which were classically and still are used for LF studies most of our knowledge is based on B- and R-band photometry. More recent work utilizes modern wide-field CCD cameras and infrared detectors to explore the LF of galaxies at other wavelengths.

Galaxies span a large range in total visual luminosity. At the extreme ends we find huge stellar systems with $L_B \sim 5 \times 10^{10} L_\odot$ ($M_B \sim -22$) such as the giant elliptical galaxy Messier 87 in the nearby VIRGO CLUSTER and the 5×10^5 times fainter dwarf elliptical galaxies Draco and Ursa Minor in the LOCAL GROUP with integrated blue light emission $M_B \sim -7.5$ comparable with a single massive main-sequence star.

The LF of galaxies is an important observational ingredient for cosmology as well as for galaxy formation and evolution. It holds fundamental information about (i) the power spectrum of the primordial density fluctuations, (ii) the physical processes that convert mass into light, e.g. gravitational collapse, cooling and star formation, and (iii) the mechanisms that destroy–generate galaxies or change their morphology such as tidal interaction, merging and ram pressure stripping. As such the LF is essential to interpret the huge apparent population of faint blue galaxies discovered at intermediate redshift ($z \approx 0.5$), to estimate the luminosity and baryonic densities of the universe and to test models of galaxy formation and evolution, e.g. the popular concept of 'biased galaxy formation'. Often the quality of a theory is assessed on how well the shape of the observed LF can be explained.

In the following we give a short historical overview about the discovery of the LF of galaxies and provide details of various observing techniques. We further explain the main features of a typical LF and discuss why nature makes LFs drawn from different parts of the universe not always look the same. We conclude with some remarks on crucial issues that are important for a deeper understanding of the LF of galaxies in the future.

A historical retrospect

The first result on the LF was published by Edwin Hubble in the mid-1930s initiated by the evidence that the velocity–apparent magnitude relation for the Shapley–Ames galaxies studied by Milton Humason exhibit only a small scatter. Interpreted in the context of a linear expansion of the universe, i.e. velocity proportional to distances (HUBBLE LAW), these observations meant that the width of the absolute magnitude distribution, i.e the LF, of these galaxies was also small. Hubble's results, although they lacked precision, suggested a Gaussian profile centered at $M_B \sim -18$ and $\sigma \sim 0.9$ mag. There seemed to be upper and lower limits for galaxy luminosities. In 1942, the validity of a bell-shaped form for the LF was called in question by Fritz Zwicky who predicted from thermodynamical considerations (principle of conservation of energy, virial theorem and Boltzmann principle) the existence of a large number of low-mass, faint dwarf galaxies in the universe and consequently a steeply rising LF towards fainter luminosities. Even though most of these dwarfs remained undetected at that time, Zwicky's idea received some support from discoveries of very faint dwarf galaxies in the Local Group.

These apparently controversial historical results exemplify the problems LF research encounters: selection bias and incompleteness. Hubble's primary goal was to measure redshifts and hence he had to concentrate on high surface brightness galaxies: ELLIPTICALS (E), LENTICULARS (S0) and SPIRALS (Sp). In this way the numerically dominant galaxy types in the universe, which we know today are the hardly visible low surface brightness DWARF IRREGULAR (dIrr) and DWARF ELLIPTICAL GALAXIES (dE), did not contribute to his consideration. Zwicky's theoretical result, on the other hand, found assistance from a spatially well-defined galaxy aggregate where the number of known dwarf galaxies was small but steadily increasing with time. Hence the Local Group catalogue reflected the actual situation much better.

Cluster versus field

When searching for galaxies across a photographic plate the eye is quickly caught by galaxy clusters which exhibit a high density contrast against the general field. Because of their nature clusters are the best places to perform LF studies. They inherit many hundreds of galaxies of all different morphological types which are all located in a small volume of space. Hence the cluster distance D, averaged over a fair number of individual known galaxy distances, can be used to convert apparent magnitudes m of all cluster members into luminosities ($M = m - 5\log[D\,(\mathrm{Mpc})] - 25$). The identification of cluster members against background and foreground objects requires the cluster to be well isolated in real and velocity space to keep contamination by non-cluster galaxies minimal. The bright E, S0 and Sp galaxies are identified based on velocity data and/or morphological criteria. At fainter luminosities most galaxies are dwarfs for which velocities are not easily accessible. The numbers of these galaxies are estimated statistically by comparing galaxy counts in a cluster with an adjacent reference field. The excess in the measured cluster LF is assigned to the cluster population. However, the heterogeneous distribution of field galaxies makes this procedure difficult and a matter of dispute. Alternatively, the unique morphological appearance of dwarf galaxies, in particular dE galaxies, provides an excellent tool to decide which object belongs to a cluster. The drawback with this method

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is the requirement for galaxy images of high angular resolution, which technically restricts the application to the closest clusters.

The field LF is much more difficult to measure. About 80% of all galaxies reside outside of rich clusters where galaxy densities are down by a factor of 100–1000. Large volumes must be surveyed to obtain representative samples of objects. Panoramic and pencil-beam surveys are carried out for this purpose using long integration times to reach low surface brightness galaxies and bright stellar systems at larger distances. Redshifts (velocities) are the backbone for field LF studies as they provide the important distance information. Employing the velocity as a distance indicator becomes possible because gravitationally induced peculiar velocities are mostly absent in the field and thus observed velocities are closely linked to the Hubble flow (the general expansion of the universe), although corrections for large-scale bulk motions are still required. Field surveys have generally an apparent magnitude limit owing to the sensitivity limits of the spectrographs. This means that intrinsically bright galaxies always predominate in galaxy samples as they are visible over large distances. To fainter luminosities the surveyed volumes shrink substantially and the galaxy numbers drop significantly. For instance the detection volume for the Small Magellanic Cloud is 4000 times smaller than for M87 just because of the difference in their total magnitudes. At that level inhomogeneities in the three-dimensional galaxy distribution do not always average out and can cause biases in the data (see DISTRIBUTION OF GALAXIES, CLUSTERS AND SUPERCLUSTERS). Various sophisticated methods exist to estimate the LF from a magnitude-limited galaxy sample (the $1/V_{\max}$, C and STY methods to name the most important ones), however the substantial corrections at the faint end of the LF make the shape in any case highly uncertain.

Overall and type-specific LFs

Since 1970 more than 100 cluster and field studies contributed to reveal the overall signature of the LF (see figure 1): after an exponential rise at $M_B \sim -22$ ($H_0 = 50$ km s^{-1} hereafter) the LF turns off at a characteristic luminosity L^* (total magnitude M^*), which is sometimes referred to as the 'knee', and follows a power law at fainter luminosities. The most popular parameterization to fit the data was proposed by Schechter in 1976:

$$\phi(L)\,\mathrm{d}L = \phi^*(L/L^*)^\alpha\ \exp(-L/L^*)\,\mathrm{d}(L/L^*) \qquad (1)$$

with the normalization parameter ϕ^*, or equivalently in magnitudes

$$\phi(M)\,\mathrm{d}M = (0.4\ln 10)\phi^* 10^{0.4(M^*-M)(1+\alpha)} \times \exp[-10^{0.4(M^*-M)}]\,\mathrm{d}M.$$

Thereby the faint-end slope is given by $-(1+\alpha)$, i.e. decreasing for $\alpha > -1$, flat for $\alpha = -1$ and increasing for $\alpha < -1$. The integral of equation (1) yields the total number of galaxies in a given volume in space whose luminosities are brighter than L: $N(> L) = \int_L^\infty \phi(L')\,\mathrm{d}L' = \phi^*\gamma(1+\alpha, L/L^*)$. Their total luminosity is $L_{tot}(> L) = \int_L^\infty L'\phi(L')\,\mathrm{d}L' = \phi^*L^*\gamma(2+\alpha, L/L^*)$, where γ is the incomplete gamma function.

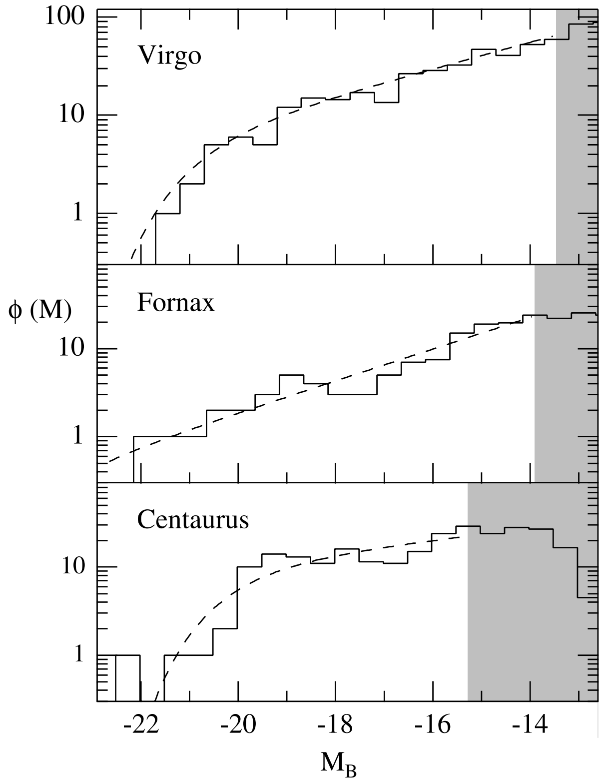

Figure 1. Data from the three clusters Virgo, Fornax and Centaurus (histograms) illustrate the diversity in observed cluster LFs. By chance Virgo is exceptionally well fitted by the Schechter form (dashed curve), whereas the local features in the LFs of Fornax and Centaurus remain unresolved. The shaded areas indicate the sample incompleteness intervals.

The Schechter function describes reasonably well the observed cluster LFs (see figure 1). Mismatches occur at the bright end owing to the presence of overluminous cluster members or if the LF is rich in local features. Nevertheless, the apparent good agreement led to the suggestion that the values $M_B^* \sim -21.0$ (about the total magnitude of the Andromeda galaxy) and $\alpha \sim -1.25$ might be of physical significance. However, this idea was not further supported by subsequent deeper surveys of clusters of various densities, richnesses, morphological classes or evolutionary stages which found a wide range of faint-end slopes ($-2.2 < \alpha < -0.9$). It was also noticed that the Schechter parameters are strongly correlated and vary significantly with the depth of a survey. The latter means that the same cluster population analyzed to different magnitude limits will not necessarily give the same Schechter parameters. Robust solutions cannot be expected above $M_B \sim -14$.

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In contrast to clusters where the signature of the environment is still imprinted on the data, the LF for field populations (including groups) gave quite a consistent picture with $M_B^* \sim -21.0$ and a flat LF down to $M_B \sim -17$. However, it is not very surprising after the previous remark that this result has been revised in recent years by deeper redshift surveys ($M_{B,lim} \sim -15$) reporting on prominent deviations from a flat LF ($-1.3 < \alpha < -0.7$). The disturbing point now is the observed scatter in α. Wouldn't we expect a well defined, unique asymptotic behavior of the field LF if averaged over a cosmological meaningful volume? This discrepancy has to be resolved in order to understand possible selection biases in the data, limitations of incompleteness corrections and eventually real differences in the dwarf-to-giant ratio for a given survey area.

After learning about all the differences between the LFs of high- and low-density regions and even among various clusters hope is dwindling that the observed spectrum of LFs can be reduced to a common denominator. However, on looking more carefully one immediate explanation comes into mind: the galaxy type mixture which intimately correlates with the environmental density. This phenomenon encompasses (1) the well-known GALAXY MORPHOLOGY–DENSITY RELATION: early-type galaxies (E, S0, dE) preponderate in the high-density regions whereas late-type galaxies (Sp, dIrr) dominate the intercluster medium, i.e. groups and field, and (2) the observation that the dwarf-to-giant ratio is correlated with the local density. These trends automatically open the question on the LFs of individual morphological galaxy types.

Our knowledge on the type-specific LFs is still in its infancy. Work started in the 1980s with first results on the Coma cluster, followed by extensive studies of the three nearby clusters Virgo, Fornax and Centaurus. Based on detailed morphological information the above-mentioned five main galaxy families could be studied individually. The results suggest that the type-specific LFs are very different but that each, except the dIrr LF, show little or no variation from one cluster to the other. The classical Hubble types E, S0 and Sp exhibit bell-shaped LFs; they exist only above a certain threshold luminosity. Dwarf galaxies are less luminous than the giants and govern completely the overall LF for galaxies fainter than $M_B \sim -16$. The large populations of dE galaxies in clusters show a steep Schechter-like LF with a mean α of -1.4. The most puzzling LF is that of the dIrrs with α values between -1.3 and -0.3. The large scatter may have its origin in the definition of the dIrr class that encompasses hardly visible low surface brightness galaxies (Im) with no or very little recent star formation activity and bright compact starburst galaxies (BCD). Difficulties in detecting the faintest members of the family can introduce selection biases to the data. However, density-dependent mechanisms that trigger star formation would also affect the LF of these gas-rich dwarfs.

The morphological resolution of field galaxies is not as accurate as for nearby cluster galaxies owing to the larger distances involved. Spectra are used instead to subdivide galaxies according to their level of star formation, a quantity that is closely related to the basic branches of early-type (E, S0, dE) and late-type (Sp, dIrr) galaxies at the present epoch. Recent deep-redshift surveys of many thousand galaxies in the redshift range $0 < z < 1$ sampled the type-specific LFs in the field as faint as $M_B = -15$. The results are qualitatively consistent with Gaussian profiles for the E–S0, and Sp galaxies and with steep LFs for dEs and dIrrs. It is interesting to note that an apparent steep dIrr LF at that magnitude limit is not necessarily in contradiction with an asymptotic value $\alpha = -1$ as illustrated in figure 2 (see 'Extreme Field'). The large number of dIrrs scales a flat dIrr LF upwards leading to a steep slope at $M_B = -15$.

The evidence for invariant type-specific LFs offers for the first time a semi-empirical tool to explore the behavior of the overall LF as a function of the environment. For this purpose the five type-specific LFs as found in three clusters (table 1) are weighted with observed and, in the case of the 'Extreme Field', hypothetic type mixtures to generate synthetic overall LFs. Similarly to working with the same ingredients but using different recipes so that the result is either a cake or a custard, this approach produces the whole range of observed LFs (see figure 2) from rich, dense clusters like Coma and loosely concentrated systems like Virgo to groups and the field. The very different characteristics of LFs from clusters to the field are explained satisfactorily with this method, which clearly indicates the importance of the type mixture and type-specific LFs for the understanding of the overall LF.

Table 1. Analytical functions and parameters that represent good first-order approximations for observed type-specific LFs in galaxy clusters. The faint-end slope for dIrrs is assumed to be -1 owing to the lack of conclusive empirical results.

E	Gauss	$\mu_B = -18.3$	$\begin{cases} \sigma_{M<\mu_B} = 2.2 \\ \sigma_{M>\mu_B} = 1.3 \end{cases}$
S0	Gauss	$\mu_B = -18.9$	$\sigma = 1.1$
Sp	Gauss	$\mu_B = -18.3$	$\sigma = 1.4$
dIrr	Schechter	$M_B^* = -16.2$	$\alpha = -1$
dE	Schechter	$M_B^* = -17.8$	$\alpha = -1.4$

Summary and prospects

Generally speaking there is a good understanding of the optical LF of galaxies down to a luminosity $M_B \sim -16$ but unfortunately this is still far away from the complete picture. The most basic detail is that the LF is the sum over separate LFs for the individual galaxy types. There are two major components in the overall LF which have been effectively discovered by Hubble and Zwicky. The first component consists of the three families of high surface brightness galaxies E, S0 and Sp. The second component is made up by the dwarfs, low surface brightness galaxies which are intrinsically

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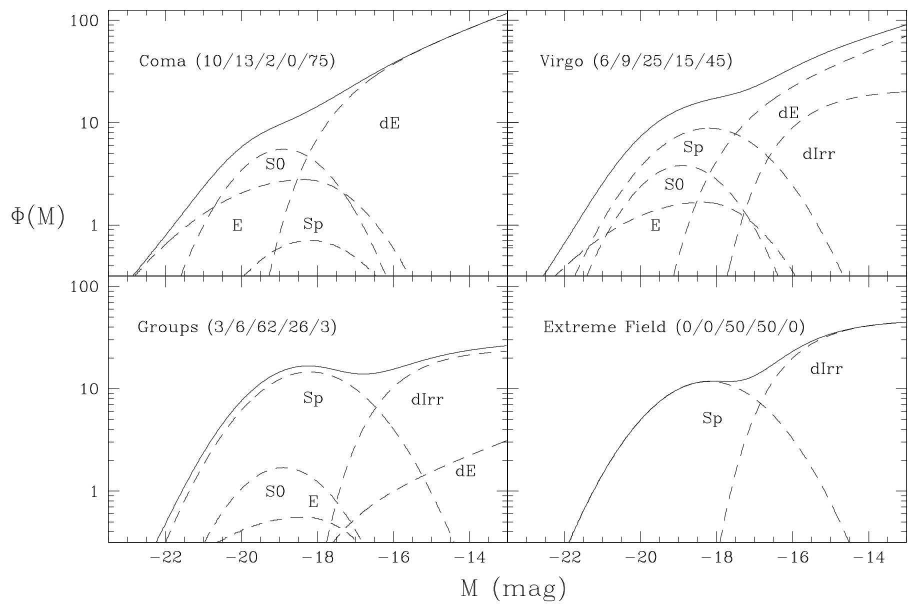

Figure 2. Synthetic overall LFs (solid curves) for four different environments with the galaxy type mixtures (E:S0:Sp:dIrr:dE) indicated as percentages. The contributions of the five main morphological types are the dashed curves.

fainter than the giants and fully control the asymptotic behaviour of the LF in all environments. This can be either a steep or moderate–flat power law depending on the local galaxy density. Due to the very different nature of the two components, many clusters (e.g. Fornax, Centaurus, Coma, Abell 963), some groups (e.g. Antlia) and field populations exhibit a prominent dip in their LFs at the transition luminosity $M_B \sim -17.5$.

Fundamentally we would like to fully understand the formation and evolution of galaxies. Results on the LF clearly indicate that this goal cannot be achieved by treating the phenomenon 'galaxy' as unity. Rather, the various morphological types have to be studied individually. From cluster work first evidence emerges that the LFs for E, S0 and Sp at the present epoch have well-defined Gaussian profiles which are unaffected by the environment. The same appears to be true for the LF of dE galaxies which follows a steep Schechter profile to all known luminosity limits. For the dIrr LF we are still lacking conclusive results as the situation is far more complex. There are some physical arguments against a single LF for dIrrs in clusters. Overall, more detailed LF studies in the local universe and at different redshifts, i.e. time epochs, are desperately needed, focusing on the separation of the morphological components in a consistent way. These results will reveal the significance of time and environmentally induced physical processes for the evolution of galaxies.

Another key issue is the variation of the morphological mixture with galaxy density and the dwarf-to-giant ratio in particular. Most current cosmological theories predict that, as the universe expands, galaxies clump together to form groups, which in turn merge together to form clusters. These 'bottom-up' scenarios have difficulties in explaining the high dwarf-to-giant ratio in clusters compared with the lower fraction in groups and the field. Where is this 'excess' of cluster dwarfs coming from? That question is fundamentally related to the space density of dIrrs which is not very well known as the faintest members of these dwarfs may remain undetected in the optical. However, this situation is going to change with systematic surveys of the local universe in neutral hydrogen (H I). dIrrs contain a substantial amount of H I gas and thus become 'visible' by their radio emission at 21 cm. Another advantage of H I surveys over optical work is that each galaxy is automatically tagged with its distance via the H I velocity. Preliminary results for nearby groups from ongoing H I surveys (e.g. HIPASS) are very promising. Many new group members have been discovered in H I but all have faint optical counterparts. Firstly this means that the average number of dIrrs and the dwarf-to-giant ratio in groups are higher than estimated to date. Secondly, the H I mass-to-light ratio for dIrrs is not increasing with fainter luminosities. The missed fraction of dIrrs per magnitude unit appears to be small which gives us greater confidence in the optical results.

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