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4. LUMINOSITY FUNCTIONS

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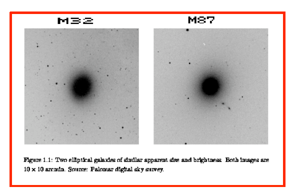
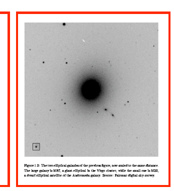
(1) Introduction

Galaxies come in a huge range of luminosity and mass : ~10^6 (M_B -7.5 to -22.5).

This is nicely illustrated by a comparison of M32 & M87





(a) as seen in the sky, and
(b) at the same physical distance

The **Luminosity Function** describes how the relative number of galaxies varies with their luminosity.

The Luminosity function contains information about :

- primordial density fluctuations
- processes that destroy/create galaxies
- processes that change one type of galaxy into another (eg mergers, stripping)
- processes that transform mass into light

Although this information is (badly) convolved, nevertheless :

- Observed LFs are fundamental observational quantities
- Successful theories of galaxy formation/evolution **must** reproduce them

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(2) Brief History

1930 Hubble notes that apparent magnitude correlates tightly with redshift (fainter galaxies have higher z).
He concludes galaxies have a narrow (Gaussian) absolute magnitude distribution : $<M_B> \sim -18$, $\sigma \sim 0.9$mag
1942 Zwicky realizes that the Local Group contains many low luminosity galaxies
He argues for a rising function for low luminosities.

As we shall see, this disagreement foreshadows two important facts :

- corrections for sample bias are **essential**
- there may be **two** types of LF; one for "normal" galaxies and one for "dwarfs"

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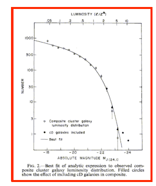
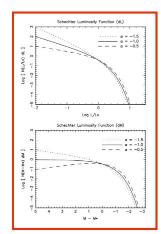
(3) The Schechter Function

In 1974 Press and Schechter calculated the **mass** distribution of clumps emerging from the young universe, and in 1976 Paul Schechter applied this function to fit the **luminosity** distribution of galaxies in Abell clusters (image). The fit turned out to be excellent, though the reasons why are still not well understood (see sec 7).



$$\Phi(L)\, dL = n_* \left(\frac{L}{L_*}\right)^{\alpha} exp\left(-\frac{L}{L_*}\right) d\left(\frac{L}{L_*}\right) \quad (4.1)$$

Be careful which version of the function is used :



- Φ(L) per dL, [which is usually plotted Log (Φ) vs Log L].
- Φ(M) per dM where M is Absolute Magnitude, so this is effectively d(logL).
- Plots may sometimes be of **cumulative** numbers: N > L or N < M.
- Compare here the Luminosity and Magnitude versions.

Observationally, it is important to specify :

- whether the LF is for specific Hubble Types, or integrated over all Types
- whether the LF if for Field galaxies or Cluster galaxies (or whatever the environment is)
- the value of H_o, since Φ varies as h^3 while L or M vary as h^{-2} where h = H_o/(100 km/s/Mpc)

Mathematically, note :

- The function has two parts :
  - a power law ($\Phi \propto L^{\alpha}$) dominates at low luminosities ($L \ll L_*$);
    index α (~ -1), so the LF **rises** as L **decreases** (ie fainter galaxies are more common)
    we use the terms "steep" for $\alpha \sim -1.5$, and "flat" for $\alpha \sim -0.5$.

- an exponential cutoff ($\Phi \propto e^{-L}$) dominates at high luminosities ($L > L_*$)
  ie very luminous galaxies are also **very rare**
- There are **three** parameters:
  - n_* : normalization, can be a number; a number per unit volume; or a probability.
    $n_* \sim 0.02\ h^3$ Mpc^{-3} for the total galaxy average.
  - α : steepness of faint end; $\alpha \sim -0.8$ to -1.3
  - L_* : luminosity at break between two regions; $L_* \sim 10^{10} L_{B\odot}\ h^{-2}$, or $M_{B,*} \sim -19.7 + 5\mathrm{Log}(h)$

- Integration over **number** gives :

$$N_{(>L)} = \int_L^\infty \Phi(L')\, dL' = n_*\, \Gamma(\alpha + 1, L/L_*) \quad (4.2)$$

where $\Gamma(a)$ is the gamma function and $\Gamma(a,b)$ is the incomplete gamma function.
For L approaching zero, $N_{tot} = n_*\, \Gamma(\alpha + 1)$ which is useful for normalizations.
Note that for $\alpha < -1$, the **total** number of galaxies **diverges** (many many dwarfs)
in reality, the LF must turn over at some lower L to avoid this

- Integration over **luminosity** gives :

$$L_{(>L)} = \int_L^\infty L'\, \Phi(L')\, dL' = n_*\, L_*\, \Gamma(\alpha + 2, L/L_*) \quad (4.3)$$

for typical α, the luminosity does **not** diverge (nor does the mass)

- Integrating from zero gives a **total** luminosity density of $L_{tot} = n_*\, L_* \Gamma(\alpha + 2)$
  Note that the integrated global LF gives a cosmologically important number :
  → for $\alpha = -1$, the luminosity density is $\sim 10^8\ h\ L_{B\odot}$ Mpc^{-3} , which for M/L ~ 10 gives :
  → a total **mass** density of $\sim 10^9\ h\ M_\odot$ Mpc^{-3} , corresponding to $\Omega \sim 0.004$

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(4) Methods of Evaluating Luminosity Functions

Cluster and field samples require quite different approaches :

(a) Cluster Samples

Since all cluster galaxies are at the same distance :

- bin galaxies by apparent magnitude, down to some limit, to get $\Phi(m)$
- use cluster redshift (distance) to get, simply, $\Phi(M)$

Complications arise principally from trying to eliminate fore/back-ground field galaxy contamination :

- velocities useful (though may still be ambiguous; dwarfs are too faint to measure)

- dwarfs (except BCDs) have **low** SB, while distant background galaxies usually have **high** SB
- apply **statistical** corrections to N(m) using field samples.

A Schechter function is fitted to Φ(M) by minimizing χ^2 to obtain M_* and α.

(b) Field Samples

In general, deriving LFs for the field is more difficult than for clusters :

- **Incompleteness** is usually found in magnitude limited samples; typically :
  - magnitude errors near m_{lim} include **fainter** galaxies
  - often, magnitude corrections (eg for internal absorption) are only applied **after** the sample is defined

  In practice, a magnitude dependent weighting factor can be applied to all galaxies to compensate for the incompleteness.
  It is possible to **check** the completeness with the V/V_{max} test :
  - V = volume out to object ; V_{max} = volume to object if pushed back to m_{lim}
  - for a **uniform density** of objects (not necessarily true !), a sample is complete for magnitude m if :
    $\langle V/V_{max} \rangle_m = 0.5$
- Corrections for Malmquist bias are **essential** (ie survey volume smaller for lower luminosity galaxies)
- Good distances are necessary (M from m), but peculiar velocities can complicate a simple linear Hubble law

Several methods have been developed :

(i) Classical Method (eg Felten 1977)

Form a histogram in absolute magnitude
Multiply the number in each bin by $1/V_{max}$
This corrects each magnitude bin to the **same effective volume**
$\rightarrow$ V_{max} is small for low luminosity galaxies, so boosts their number to compensate
Unfortunately, this method **assumes a constant space density**
This certainly isn't true (e.g. local group dwarfs are over represented locally).

(ii) Differential/Cumulative Ratio Method (e.g. Kirshner et al 1979)

This method avoids the previous assumption of uniform density.
However, it does assume that the shape of the LF doesn't depend on environment, ie

- N(M) = Φ(M) x D(x,y,z), where D(x,y,z) is a position dependent total galaxy density, and Φ(M) is the LF expressed as a **probability**

Because N(>M) is the integral of N(M), then N(M)/N(>M) = Φ(M)/ Φ(>M) since D(x,y,z) cancels
Consequently, Φ(M)/ Φ(>M) is **independent of D(x,y,z)**
basically : for a given region, if N(M) is high because of the density, then so is N(>M)
Now, Φ(M) and Φ(>M) are evaluated **using the the classical method**
Either their ratio is fitted with the equivalent ratio of a Schechter function, or
a smooth function is fitted, whose differential is fitted to a Schechter function.

(iii) The C method (eg Lynden-Bell 1971, revised by Choloniewski 1987)

This method was first devised and applied to quasars.
It only assumes spherical symmetry (but not constant density)
Consequently it is best applied to **pencil beam surveys**

The method is supposedly simple and elegant, but I can't understand it
It involves expressing $\Phi(M)$ and $D(r)$ as the sums of weighted delta functions, then somehow evaluating the weighting factors using "C-functions"......??

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(5) Different LFs for Different Hubble Types

Early work showed :

- Schechter function is a good fit to many galaxy samples, **but**
- the parameters (L_*, α) can vary depending on : sample depth, cluster or field, cluster type

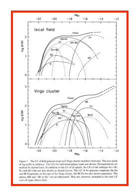
Recently, things are becoming clearer :

- it is important to consider the LFs of different galaxy **Types**.
- it now seems that the LFs of the major galaxy types are
  - different from eachother
  - relatively independent of environment
- it is the relative **proportions** of each galaxy type that vary between cluster and field (see next section)

More specifically, broken down by type, we have the following LFs :

- Spirals (Sa - Sc) : Gaussian, $\langle M_B \rangle \sim -16.8 + 5\log(h)$, $\sigma \sim 1.4$ mag
- S0 galaxies : Gaussian, $\langle M_B \rangle \sim -17.5 + 5\log(h)$, $\sigma \sim 1.1$ mag
- Ellipticals : Skewed Gaussian (to bright), $\langle M_B \rangle \sim -16.9 + 5\log(h)$
- dwarf Ellipticals (dE+dSph) : Schechter function, $M_* \sim -16 + 5\log(h)$, $\alpha \sim -1.3$
- dwarf Irregulars (dIrr): Schechter function, $M_* \sim -15 + 5\log(h)$, $\alpha \sim -0.3$

These LFs are illustrated here for the Field and Virgo.
Clearly, full sample LFs :



- have a steep cutoff due to the Gaussian LF of the luminous Spirals, S0s and Ellipticals
- have rising faint end due to dEs (and to lesser extent dIrr).

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(6) Different LFs for Field and Clusters

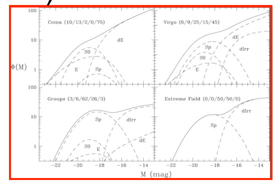
Evaluating LFs for Clusters is reasonably straightforward since the galaxies are all at the same distance.

In general, cluster LFs :

- are well fit by a Schechter function
- have similar L_*, though α can vary, and is often steeper than in the field (~ -1.3)
- there can be a dip/drop near $M_B \sim -16 + 5\log(h)$
- there can be an excess at higher luminosities
- cD galaxies (~$10L_*$) dont fit, and would be considered outliers in **any** smooth distribution.

We can now understand much of this :

- different LFs usually arise from different **proportions** of Sp, S0, E, dE, and dIrr
- specifically, more E, S0, dEs are in clusters, while more Spirals and dIrr are in the field, this is evidence for a **morphological dependence on galaxy density** (see figure).
- the dip at $M_B \sim -16$ occurs at the changeover from "normal" to "dwarf" galaxies
- cD galaxies have clearly had a different history, probably growing by accretion in dense galactic environments.



See Topic 16 § 7 for a discussion of the physical origin of the morphology-density relation.

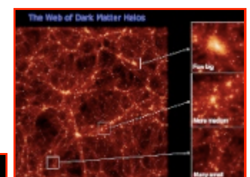
(7) Physical Origin of the Luminosity Function

Why does the galaxy luminosity function have the form that it does?
A complete understanding of this is not yet possible, but here are the ingredients:
Making galaxies involves at least **two** things

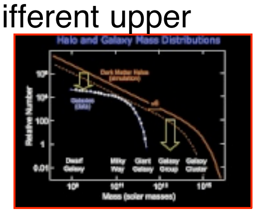
- dark matter halos must form (relatively straightforward)
- baryons must fall in and make stars (complex physics)

Here is a very brief account:

- Cosmological simulations follow cold dark matter from initial slight perturbations to make many halos by hierarchical assembly.
- The **mass distribution** of these halos follows the Schechter form [this was Press and Schechter's 1974 analytic result]. Hence one might expect a Schechter function for the **galaxy** mass distribution (see figure)



- However, the **observed** galaxy mass function has completely different upper cutoff and lower slope (see figure). Specifically, there are too many huge and dwarf halos without huge and dwarf galaxies.



- To understand why, we need to look at what prevents baryons from making stars within halos of different size (see figure).
  a. Gas falling into huge halos is too hot to cool.
     This becomes the intercluster medium in galaxy clusters.
  b. Gas falling into less massive halos is kept hot by AGN jets
  c. Gas falling into small halos can be easily blown out by supernovae and star winds
  d. Gas cannot fall into tiny halos -- it is prevented by its own pressure.
- These processes are added to the cosmological dark matter simulations using simple prescriptive formulae, to generate so-called: "semi-analytic models" (see figure).
- These nicely reproduce many galaxy demographic results, including a galaxy mass function that is a much better match to the galaxy luminosity function.