Whittle : EXTRAGALACTIC ASTRONOMY

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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).

Look at any galaxy cluster, and you see a wide range of galaxy luminosities [image]
The **Luminosity Function** specifies the relative number of galaxies at each 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: $\langle M_B \rangle \sim -18$, $\sigma \sim 0.9$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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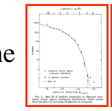
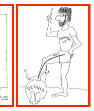
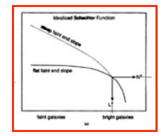
(3) The Schechter Function

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).

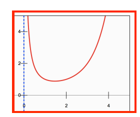
$$\Phi(L)\,dL = n_* \left(\frac{L}{L_*}\right)^{\alpha} exp\left(-\frac{L}{L_*}\right)\, d\left(\frac{L}{L_*}\right) \qquad (4.1)$$

- The function has **two** parts and **three** parameters: [image]
  - L_* : luminosity that separates the low & high luminosity parts;
    $L_* \sim 10^{10}\, L_{B\odot}\, h^{-2}$, or $M_{B,*} \sim -19.7 + 5\mathrm{Log}(h)$



  - At low luminosity, ($L < L_*$): We have a power law ($\Phi \propto L^{\alpha}$)
    $\alpha \sim -0.8$ to -1.3 ("flat" to "steep")
    $\rightarrow$ lower luminosity galaxies are more common.
  - At high luminosity, ($L > L_*$): We have an exponential cutoff, ($\Phi \propto e^{-L}$)
    $\rightarrow$ very luminous galaxies are very rare
  - n_* : is a normalization, set at L_*
    $n_* \sim 0.02\, h^3\, \mathrm{Mpc}^{-3}$ for the total galaxy population.
    Depending on context, n_* can be a number; a number per unit volume; or a probability.
    Note the implicit dependence on Hubble constant, via h^3.
- Integration over **number** gives:

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



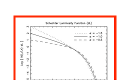
where $\Gamma(a)$ is the gamma function [image] and $\Gamma(a,b)$ is the incomplete gamma function.
For $L \rightarrow 0$, the total number of galaxies, $N_{tot} = n_*\, \Gamma(\alpha + 1)$.
Note that for $\alpha \leq -1$, N_{tot} **diverges** (many many dwarfs)
In reality, the LF must turn over at some lower L to avoid this

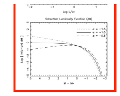
- Integration over **luminosity** gives :

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

Integrating from zero gives a **total** luminosity density of $L_{tot} = n_*\, L_*\, \Gamma(\alpha + 2)$
For typical α, the luminosity does **not** diverge (nor does the mass)

- Note that the integrated global LF gives a cosmologically important number:
  $\rightarrow$ for $\alpha = -1$, the luminosity density is $\sim 10^8\, h\, L_{B\odot}\, \mathrm{Mpc}^{-3}$, which for $M/L \sim 10$ gives:
  $\rightarrow$ a total **mass** density of $\sim 10^9\, h\, M_{\odot}\, \mathrm{Mpc}^{-3}$, corresponding to $\Omega_* \sim 0.004$
  We conclude that stars/galaxies contain ~10% of all baryons (since $\Omega_{bary} \sim 0.04$)
  (The rest is thought to be in the IGM).
- Be careful which version of the luminosity function is used: [image]
  - $\Phi(L)$ 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).
  - Sometimes the **cumulative** LF is given: N > L or N < M.

- Observationally, it is also important to specify:
  - whether the LF is for specific Hubble Types, or integrated over all Types
  - whether the LF is 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)

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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 Φ(m)
- use cluster redshift (distance) to get, simply, Φ(M)
- Fit a Schechter function to Φ(M) by minimizing χ^2 to obtain M_* and α.

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

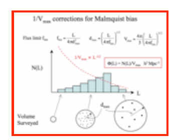
- velocities useful (though may still be ambiguous; dwarfs are too faint to measure)
- dwarfs (except BCDs) have **low** SB, while distant background galaxies usually have **high** SB
- apply **statistical** corrections to N(m) using field samples.

(b) Field Samples

In general, deriving LFs for the field is more difficult than for clusters:
Many methods have been developed, here is the simplest:

(i) Classical Method (eg Felten 1977)

Obtain a **flux limited** sample: all galaxies brighter than given magnitude limit.
Use distances to calculate luminosity of each galaxy
Form a histogram in luminosity: N(L).



However, each luminosity bin comes from a different survey volume (Malmquist bias): [image].
e.g. surveyed volume, V_{max}(L), is small (large) for low (high) luminosity objects
So divide N(L) by V_{max}(L) to create Φ(L) the **density** of objects at each luminosity.
This now corrects the Malmquist bias and each luminosity samples the same effective volume.

Unfortunately, this method **assumes a constant space density**
For nearby samples, this isn't such a good approximation.

(ii) Maximum Likelihood Method

Most modern work uses a "maximum likelihood" approach (e.g. SDSS).
A flux limited sample is a list of galaxies, each with distance d_i and luminosity L_i
Consider the minimum luminosity, $L_{min}(d_i)$, that could be in the sample, i.e. above the flux limit.
The relative number of galaxies of **any** luminosity that could be at that distance, d_i is:

$$\int_{L_{min}(d_i)}^{\infty} \Phi(L)\, dL \qquad (4.4)$$

So the **probability**, p_i, that the galaxy actually has luminosity L_i is given by:

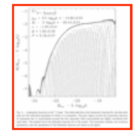
$$p_i = \left(\frac{\Phi(L_i)}{\int_{L_{min}(d_i)}^{\infty} \Phi(L)\, dL} \right) \qquad (4.5)$$

One now defines a **liklihood function**, $\mathcal{L}$, giving the joint probability of finding all L_i at their respective distances d_i:

$$\mathcal{L} = \prod_i p_i \qquad (4.6)$$

If $\Phi(L)$ is parameterized by a Schechter function, then one varies L_* and α so as to maximize $\mathcal{L}$.
These are now the most likely parameters consistent with the data and a Schechter form.

One can fit **any** function this way: e.g. a set of values of $\Phi_k(L)$ specified at K luminosity bins: Φ_k (k=1,2,3....K).
This is how the SDSS data were analyzed by Blanton et al 2003: o-link [image]



(iii) Testing Completeness with < V/V$_{max}$ >

In addition to Malmquist bias, samples can be **incomplete** for other reasons:

- magnitude errors near m_{lim} include **fainter** galaxies
- often, magnitude corrections (e.g. for internal absorption) are only applied **after** the sample is defined

In practice, magnitude dependent weighting factors are applied to compensate for the incompleteness.

It is possible to **check** for completeness with the V/V_{max} test:
For each galaxy, find the ratio V / V_{max} where:

- V is the volume out to that galaxy
- V_{max} is the volume out to d_{max}, the distance that the galaxy would be at the flux limit.

If the average of that ratio, $< V / V_{max} > = 0.5$ then the sample is complete.
One can also separate the sample into bins of apparent magnitude,
When $< V / V_{max} >_m$ begins to deviate from 0.5 you've hit the completeness limit of the survey.

Unfortunately, this test also assumes a constant space density.

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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 :

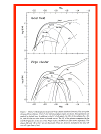
- it is important to consider the LFs of different galaxy **Types**.
- it now seems that the LFs of the major galaxy types are
  - different from eachother
  - relatively independent of environment
- it is the relative **proportions** of each galaxy type that vary between cluster and field (see next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

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

- Spirals (Sa - Sc) : Gaussian, $<M_B> \sim -16.8 + 5\log(h)$, $\sigma \sim 1.4$ mag
- S0 galaxies : Gaussian, $<M_B> \sim -17.5 + 5\log(h)$, $\sigma \sim 1.1$ mag
- Ellipticals : Skewed Gaussian (to bright), $<M_B> \sim -16.9 + 5\log(h)$

- dwarf Ellipticals (dE+dSph) : Schechter function, $M_* \sim -16 + 5\log(h)$, $\alpha \sim -1.3$
- dwarf Irregulars (dIrr): Schechter function, $M_* \sim -15 + 5\log(h)$, $\alpha \sim -0.3$

LFs for the Field and Virgo are illustrated here: [image].
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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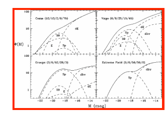
(6) Different LFs for Different Environments

It seems the LFs of galaxies in clusters can be different from galaxies in the field.
In general, cluster LFs :

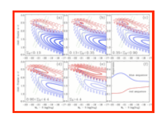
- are well fit by a Schechter function
- have similar L_*, though α can vary, and is often steeper than in the field (~ -1.3)
- there can be a dip/drop near $M_B \sim -16 + 5\log(h)$
- there can be an excess at higher luminosities
- cD galaxies (~$10L_*$) dont fit, and would be considered outliers in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

Analysis of the SDSS shows similar results, but cast in terms of the red and blue sequences [image]



- At higher galaxy density, the relative populations of red and blue galaxies shifts
- There are more high-luminosity red galaxies
- This is consistent with a transformation from blue sequence to red sequence

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

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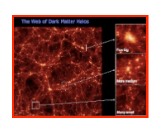
(7) Physical Origin of the Luminosity Function

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

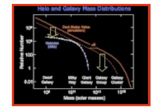
- dark matter halos must form (relatively straightforward)
- baryons must fall in and make stars (complex physics)

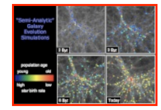
Here is a very brief account:



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

- To understand why, we need to look at what prevents baryons from making stars within halos of different size.
  - Gas falling into huge halos is too hot to cool. [image]
    This becomes the intercluster medium in galaxy clusters.
  - Gas falling into less massive halos is kept hot by AGN jets
  - Gas falling into small halos can be easily blown out by supernovae and star winds
  - 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" [image].
- These nicely reproduce many galaxy demographic results, including a galaxy mass function that is a much better match to the observed galaxy luminosity function.

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