Galaxies: Structure, formation and evolution

Lecture 5

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Question

We saw that successful models of structure formation need to reproduce the observed correlation function/power spectrum on all length scales. Is there any other global observable, that models need to reproduce correctly?

Luminosity functions

The Luminosity Function specifies the relative number of galaxies at each luminosity.
The Luminosity function is a convolution of many different effects:

- primordial density fluctuations
- processes that destroy/create galaxies
- processes that change one type of galaxy into another (e.g. galaxy mergers)
- processes that transform mass into light

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

Seminar paper- extending date to 30 Jan

Mid term exam

will be based on the first 6 lectures, and will have a weightage of 25%.
I propose to have the exam on 31 Jan afternoon.

The luminosity function

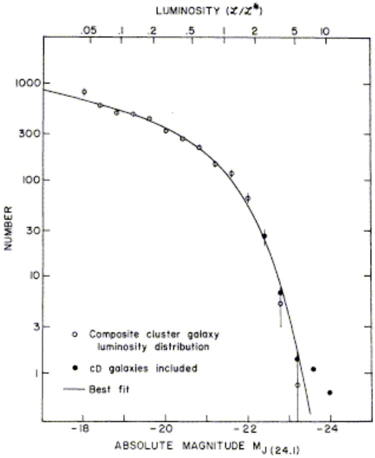


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

Schecter Luminosity 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.

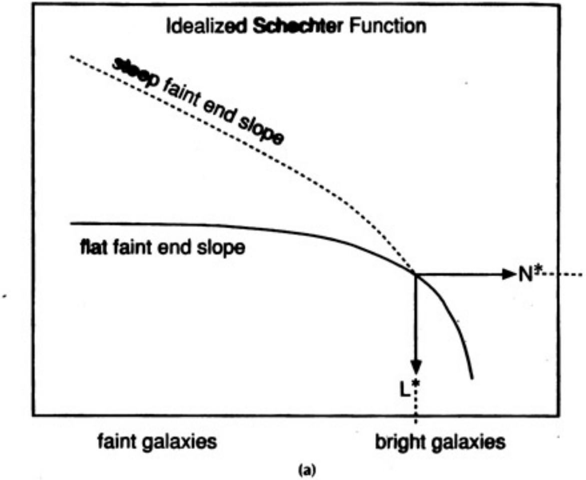
$$\phi(L)dL = n_* \left(\frac{L}{L_*}\right)^{\alpha} exp\left(-\frac{L}{L_*}\right) d\left(\frac{L}{L_*}\right) \quad (1)$$

Function has two parts and three parameters.

Schecter Luminosity function

- L_* : luminosity that separates the low and high luminosity parts; $L_* \sim 10^{10} L_{B\odot} h^{-2}$, or $M_{B,*} \sim -19.7 + 5\log(h)$
- At low luminosity, ($L < L_*$): We have a power law with $\alpha \sim -0.8$ to -1.3 ("flat" to "steep") lower luminosity galaxies are more common.
- At high luminosity, ($L > L_*$): We have an exponential cutoff, very luminous galaxies are very rare
- n_* : is a normalization, set at L_* $n_* \sim 0.02h^3$ 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.

What each parameter does



Properties of the luminosity function

$$N_{(>L)} = \int_L^\infty \phi(L')dL' = n_* \Gamma(\alpha + 1, L/L_*) \qquad (2)$$

For $L \to 0$, the total number of galaxies, $N_{\rm tot} = n_* \Gamma(\alpha + 1)$. What happens for $\alpha \leq -1$?
Integrating over luminosity,

$$L_{(>L)} = \int_L^\infty L'\phi(L')dL' = n_* L_* \Gamma(\alpha + 2, L/L_*) \qquad (3)$$

Different equivalent forms of the luminosity function

$\phi(L)$ per dL, (which is usually plotted $\log(\phi)$ vs $\log L$). $\phi(M)$ per dM where M is absolute magnitude, so this is effectively $d(\log L)$. Sometimes the cumulative LF is given: $N > L$ or $N < M$. So please check the axes on your plots.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_0, since ϕ varies as h^3 while L or M vary as h^{-2}

How to measure the luminosity function? in Clusters

All cluster galaxies are at the same distance.

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All cluster galaxies are at the same distance.

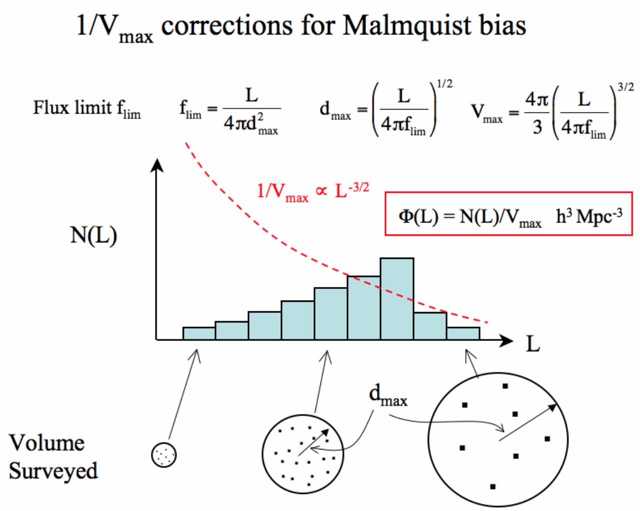
1. bin galaxies by apparent magnitude, down to some limit, to get $\phi(m)$
2. use cluster redshift (distance) to get $\phi(M)$
3. Fit a Schechter function to $\phi(M)$ by minimizing χ^2 to obtain M_* and α.

Complications arise principally from trying to eliminate fore/back-ground field galaxy contamination: here galaxy velocities are useful. Also dwarfs are often too faint to measure (except BCDs) because they have low SB. We need to apply statistical corrections to $N(m)$ using field samples.

Measuring the LF in the field

Obtain a **flux limited** sample: all galaxies brighter than given apparent magnitude limit. Use distances to calculate luminosity of each galaxy. Form a histogram of luminosity: $N(L)$.
However, each luminosity bin comes from a different survey volume (Malmquist bias) i.e. surveyed volume, $V_{max}(L)$, is small (large) for low (high) luminosity objects. So divide $N(L)$ by $V_{max}(L)$ to create $\phi(L)$ 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. When will this assumption be especially problematic?

Correcting Malmquist bias



Maximum likelihood method

See: Blanton et al. 2003, ApJ, 592, 819 *To estimate the luminosity function, we use a maximum likelihood method that allows for a general form for the shape of the luminosity function, fits for simple luminosity and number evolution, incorporates the flux uncertainties, and accounts for the flux limits of the survey.*

This is the method most commonly used today.

The V/V_{max} test to check for completeness

In addition to Malmquist bias, samples can be incomplete for other reasons: magnitude errors near m_{lim} include fainter galaxies and 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, $\langle V/Vmax \rangle = 0.5$ then the sample is complete Why 0.5?. We separate the sample into bins of apparent magnitude, When $\langle V/Vmax \rangle$ begins to deviate from 0.5 you've hit the completeness limit of the survey.
Unfortunately, this test also assumes a constant space density.

Schecter LF

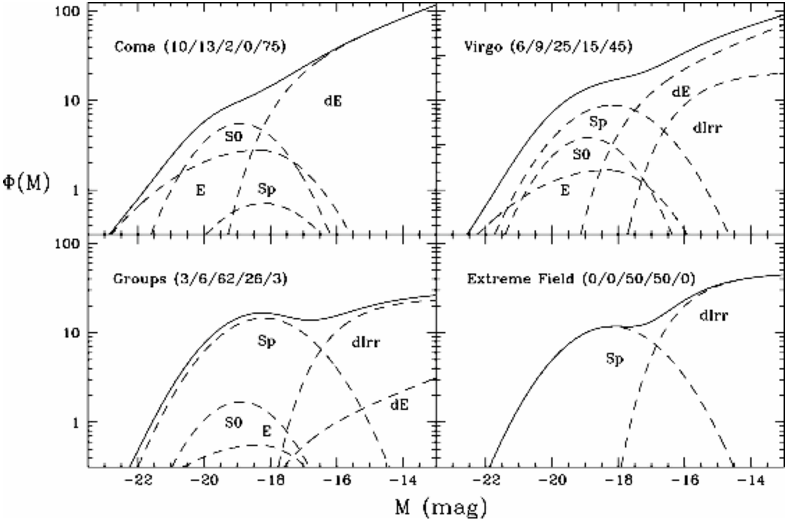
Early work showed that the Schechter function is a good fit to many galaxy samples, but the parameters (L_*,α) can vary depending on: sample depth, cluster or field, cluster type, morphological type. **Which one is more important?**

In general, cluster LFs are well fit by a Schechter function have similar L*, α is often steeper than in the field ($\sim$ -1.3), there can be a dip/drop near $M_B \sim -16 + 5\log(h)$, there can be an excess at higher luminosities for cD galaxies ($\sim 10L_*$).

Understanding the cluster LF

Recent research shows that 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 - the **morphology density relation** (Dressler 1980). 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.

Decomposing LF by morphology



Abell 1689 - cD galaxy more luminous than LF predicts

This was already discovered by Schecter (1976)!

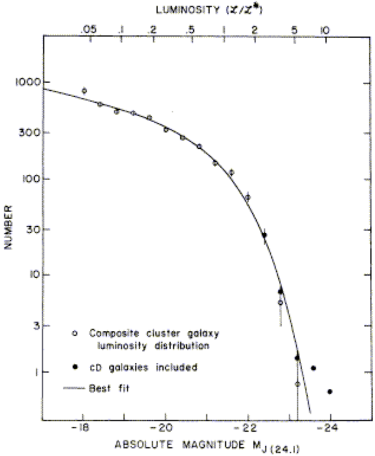


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

Physical origin of the LF

Making galaxies involves at least two steps.

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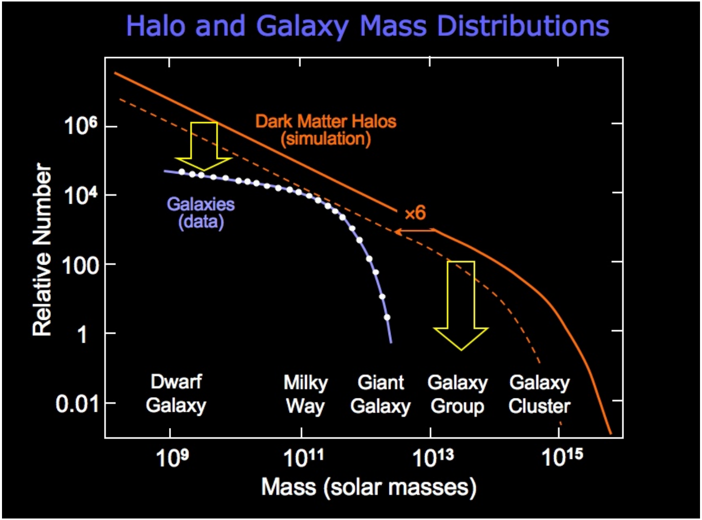
Making galaxies involves at least two steps.

1. dark matter halos must form (relatively straightforward and well understood)
2. baryons must fall in and make stars (complex physics)

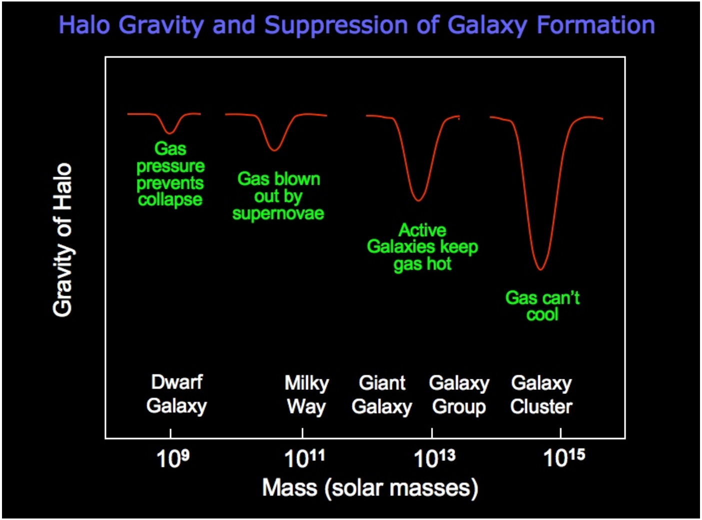
Cosmological simulations follow cold dark matter from initial slight perturbations to make many halos by hierarchical assembly. The mass distribution of these halos follows the Schechter form (Press & Schecter 1974). Hence one might expect a Schechter function for the galaxy mass distribution. Under what assumption?
The **observed** galaxy mass function has completely different upper cutoff and lower slope. Specifically, there are too many huge and dwarf halos (in simulations) without huge and dwarf galaxies (in the real universe).

Too many haloes too few galaxies

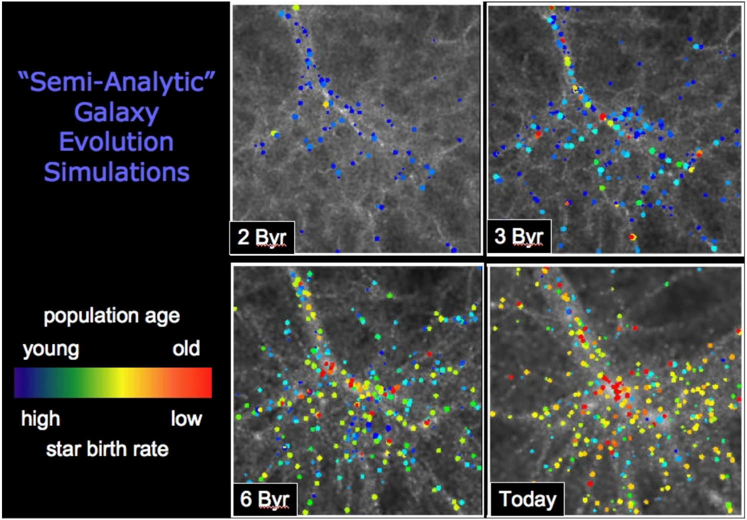


See: http://www.illustris-project.org/

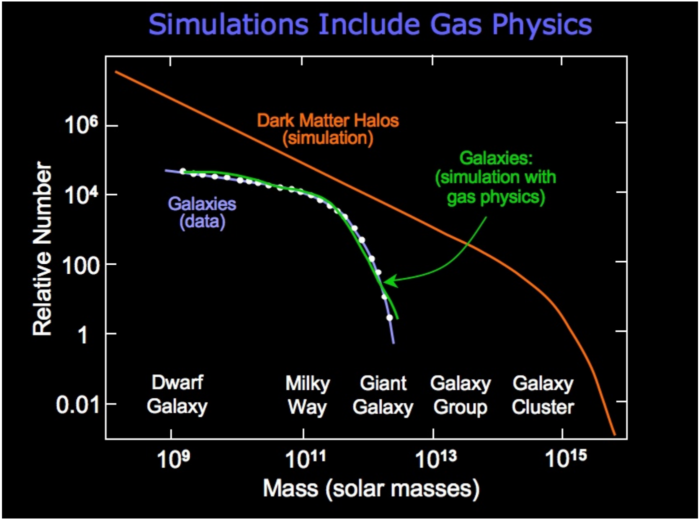
Schematic explanation of the halo galaxy mismatch



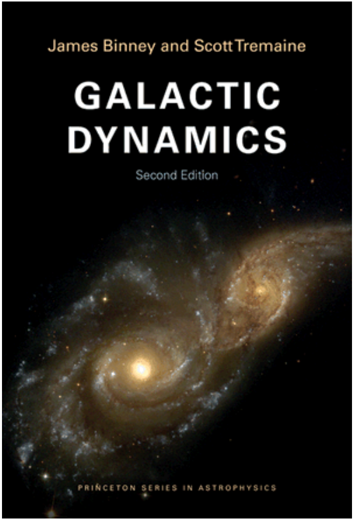
Semi analytic models



Semi analytic models reproduce the observed LF well



Binney and Tremaine - Galaxy Dynamics



Disk galaxies

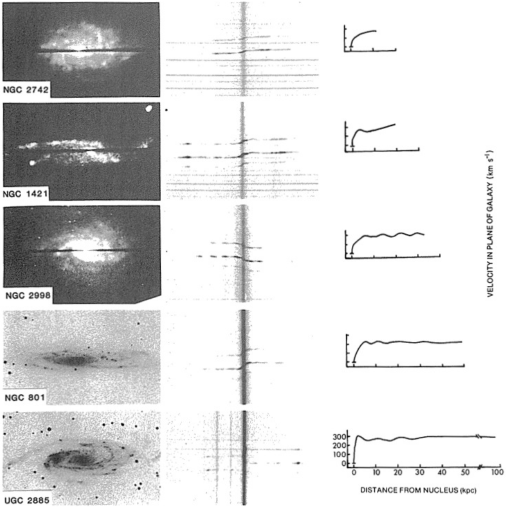
- stellar populations: old, intermediate, young and currently forming with ongoing chemical enrichment
- Wide range in stellar dynamics: “cold” rotationally supported disk stars , “hot” mainly dispersion supported bulge and halo stars. How to quantify hot and cold in dynamics?
- Significant “cold” ISM

Vertical disk structure - in edge on disk galaxies

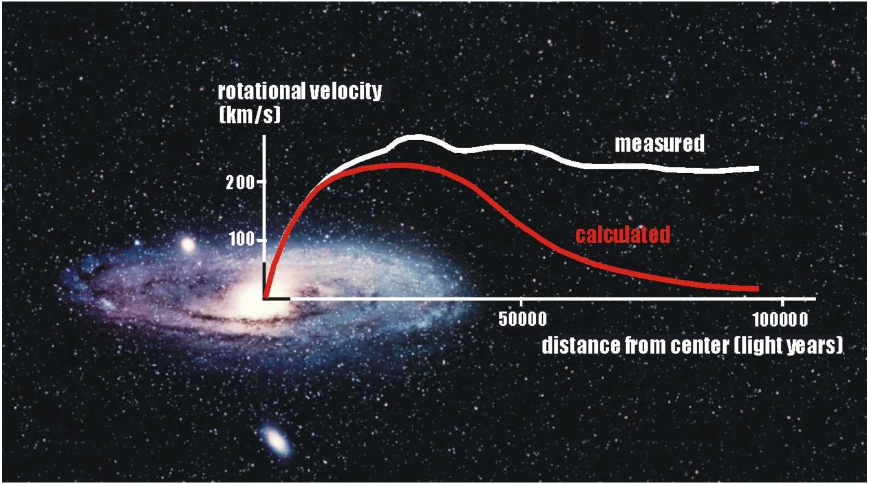
$$I(z) = I(0)e^{-|z|/z_0} \tag{4}$$

where z_0 is the scale height of the disk. In some galaxies, a thick disk with larger scale height is also seen. How should the vertical variation be modeled in such galaxies?

Spiral rotation curves



Why dark matter must be present?



3 major modes of optical spectrocopy

- 1D spectroscopy - “0D” fiber input is dispersed, producing a 1D spectrum

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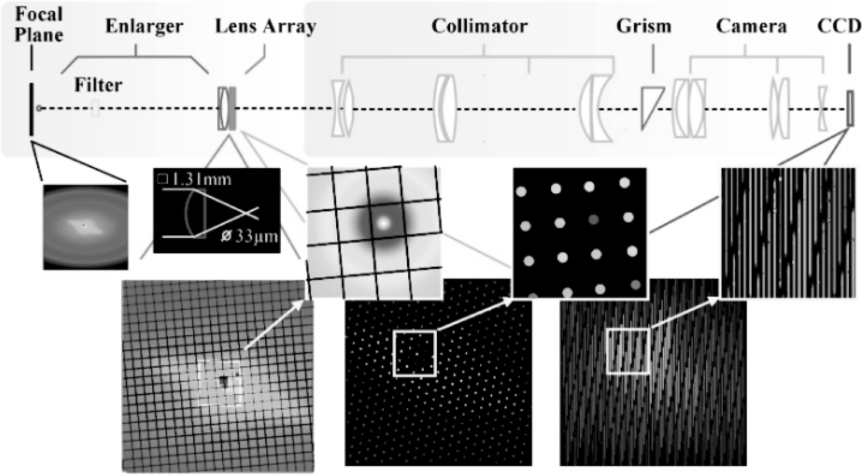
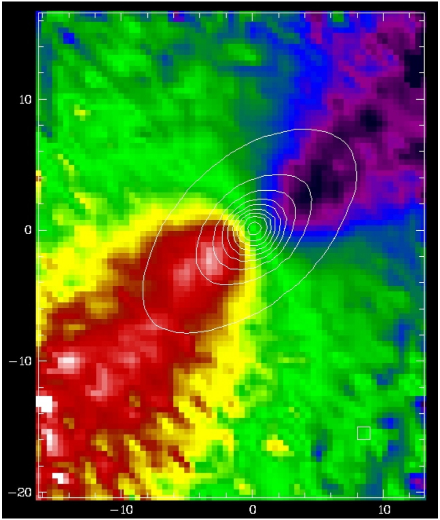
- 2D spectroscopy - “1D” slit input is dispersed producing a 2D spectrum.
- 3D spectroscopy - “2D” lenslets/bundled fibres input is dispersed producing a 3D spectrum (data cube)

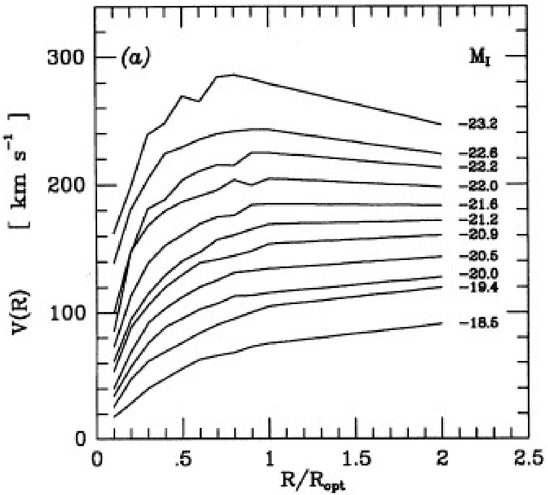
Sauron 3D spectroscopy



IFU spectrum



Rotation curves at different luminosities



As luminosity increases, the rotation amplitude increases; the initial rise steepens; the outer slope drops.

In the inner region

For luminous early type spirals, $V(r)$ rises very rapidly. $\rightarrow$ bulge more important.

For low luminosity later type spirals, $V(r)$ rises more slowly often $V(r) \propto r$ "solid body".

In the "hypothetical situation" where the supermassive black hole at the center contained most of the mass of the galaxy and there was no dark matter, how would $V(r)$ look?

Question

How to use circular velocities to measure mass within a certain radius?

Measuring the mass of galaxies for spherical symmetry case

Motions of stars and gas in the disc of a spiral galaxy are more or less circular (V_R and $V_Z << V_R$)
Acceleration of the star moving in a circular orbit must be balanced by the gravitational force. Hence force on a unit mass is:

$$\frac{V^2(r)}{r} = -F_r(r) \tag{5}$$

To calculate $F_r(r)$, we need to sum up all gravitational force from bulge, disk and halo. If the mass within radius r is $M(r)$, gravitational force on a unit mass is:

$$F_r = -\frac{GM(r)}{r^2} \tag{6}$$

From observed $V(r)$, we can infer $M(r)$.

Mass of a pure thin exponential disk

$V_c^2(R) = R\frac{\partial\phi}{\partial R}$ Solving this diff. equation results in a solution that includes modified Bessel functions of the first and second kind which simplify to:

$$V_c^2(R) = 0.767\frac{GM_d}{R_d}\frac{0.44(R/R_d)^{1.3}}{1 + 0.235(R/R_d)^{2.3}}, R < 4R_d$$

This rotation curve has peak at $R\mathrm{max} \sim 2.2R_d$, for $R > 3R_{\mathrm{max}}$ curve is Keplerian
See section 2.6 of B&T for the full details.

Milky way rotation curve

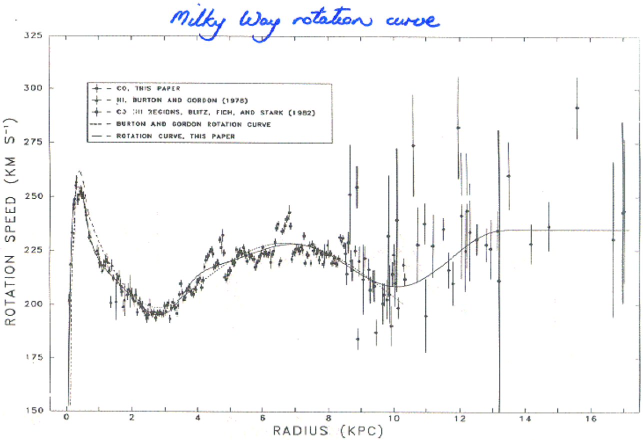


FIG. 3.—Plots of the rotation speed versus galactocentric radius. The solid lines correspond to the polynomials, and the dashed lines are the BG rotation curve. (*upper panel*) $(R_0, \theta_0) = (10$ kpc, 220 km s^{-1}); (*lower panel*) (8.5 kpc, 220 km s^{-1}).