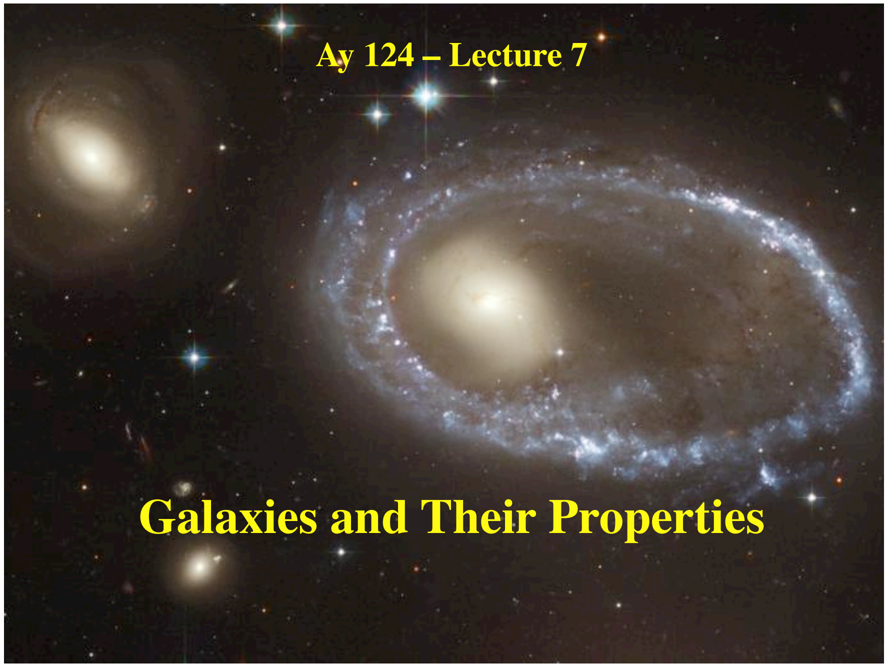


Ay 124 – Lecture 7

Galaxies and Their Properties

Galaxies

- The basic constituents of the universe at large scales
  - Distinct from the LSS as being too dense by a factor of $\sim 10^3$, indicative of an "extra collapse", and a dissipative formation
- Have ***a broad range of physical properties***, which presumably reflects their evolutionary and formative histories, and gives rise to various morphological classification schemes (e.g., the Hubble type)
- Understanding of galaxy formation and evolution is one of the main goals of modern cosmology
- There are $\sim 10^{11}$ galaxies within the observable universe
- Typical total masses $\sim 10^8$ - $10^{12}\ M_\odot$
- Typically contain $\sim 10^7$ - 10^{11} stars

Catalogs of Bright Galaxies

- In late 1700's, **Messier** made a catalog of 109 nebulae so that comet hunters wouldn't mistake them for comets!
  - About 40 are galaxies, e.g., M31, M51, M101; many are gaseous nebulae within the Milky Way, e.g., M42, the Orion Nebula; some are star clusters, e.g., M45, the Pleiades
- **NGC** = New General Catalogue (Dreyer 1888), based on lists of Herschel (5079 objects), plus some more for total of 7840 objects
  - About ~50% are galaxies, catalog includes any non-stellar object
- **IC** = Index Catalogue (Dreyer 1895, 1898): additions to the NGC, 6900 more objects
- Shapley-Ames Catalog (1932), rev. Sandage & Tamman (1981)
  - Bright galaxies, $m_{pg} < 13.2$, whole-sky coverage, fairly homogenous, 1246 galaxies, all in NGC/IC

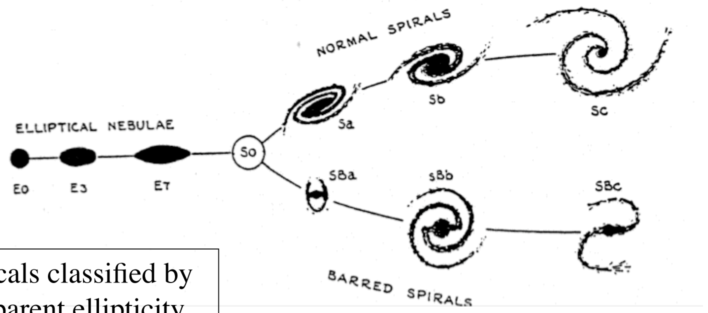
Catalogs of Bright Galaxies

- **UGC** = Uppsala General Catalog (Nilson 1973), ~ 13,000 objects, mostly galaxies, diameter limited to > 1 arcmin
  - Based ased on the first Palomar Observatory Sky Survey (POSS)
- **ESO** (European Southern Observatory) Catalog, ~ 18,000 objects
  - Similar to UGC, 18000 objects
- **MCG** = Morphological Catalog of Galaxies (Vorontsov-Vel'yaminov et al.), ~ 32,000 objects
  - Also based on POSS plates, $-2° < \delta < -18°$
- **RC3** = Reference Catalog of Bright Galaxies (deVaucoleurs et al. 1991), 23,022 galaxies, magnitude limited to B < 15.5
  - Essentially a heterogeneous data compilation
  - Preceded by RC1 (1964, 2599 galaxies) and RC2 (1976, 4364 galaxies)
- Nowadays we have automated surveys, e.g., DPOSS, SDSS, with tens to hundreds of millions of galaxies; and this will grow…

Morphological Classification and Galaxy Types

- The first step in any empirical science: look for patterns and trends, then try to understand the underlying physics
- Hubble proposed a scheme for classifying galaxies (the “tuning fork” diagram) in his 1936 book, *The Realm of the Nebulae*
- Subsequent refinements proposed by de Vaucouleurs (T-types), van den Bergh, and others - but not any fundamental change
- Nowadays we seek to define galaxy families through their physical properties and fundamental correlations - which reflect their physics and formative histories
- A better approach may be to look at the properties of *subsystems* within galaxies (e.g., disks, spheroids, halos, etc.), and deduce their origins and evolution

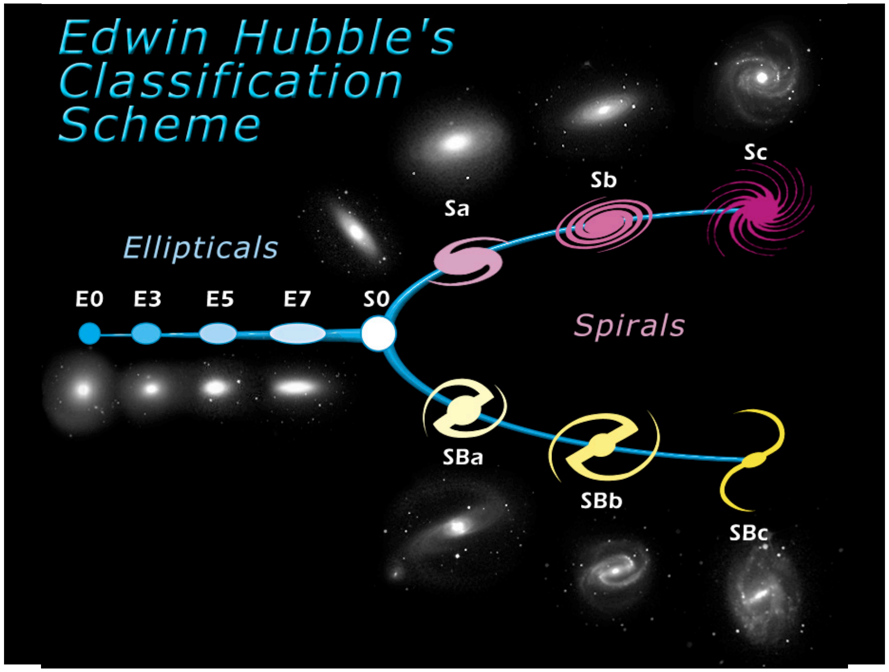
Hubble’s Classification Scheme



Ellipticals classified by the apparent ellipticity

Spirals classified by the prominence of the spiral arms, and the presence of bars

Hubble thought (incorrectly) this was an evolutionary sequence, so ellipticals are called “early-type” and spirals “late-type” galaxies

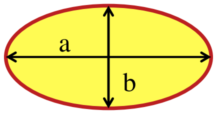


Elliptical Galaxies

- About 20% of field galaxies are E’s, but most E’s are in clusters
- There are a number of different subtypes:
  - E’s (normal ellipticals)
  - cD’s (massive bright ellipticals at the centers of galaxy clusters)
  - dE’s (dwarf ellipticals)
  - dSph’s (dwarf spheroidals)

  } Not really ellipticals, a different class of objects
- Smooth and almost featureless: no spiral arms or dust lanes. Generally lacking in cool gas, and hence few young blue stars
- Classified by the apparent ellipticity:

$$\varepsilon = 1 - \frac{b}{a}$$



Elliptical galaxies are denoted E*n*, where:

$$\frac{b}{a} = 1 - \frac{n}{10}$$

A round elliptical is E0, the most elongated ellipticals are E7

Elliptical Galaxies

M87 in Virgo

M84 and M86

Lenticular (S0) Galaxies

- Transition class between ellipticals and spirals are the S0 galaxies, also called **lenticulars**
- S0 galaxies have a rotating disk in addition to a central elliptical bulge, but the disk lacks spiral arms or prominent dust lanes, i.e., no active star formation
- Lenticulars can also have a central bar, in which case they are labeled SB0

Sombrero galaxy

Spiral Galaxies

Named for their bright spiral arms, which are prominent due either to bright O and B stars (evidence for recent star formation), or to dust lanes.

Define two parallel sequences of spiral galaxies:

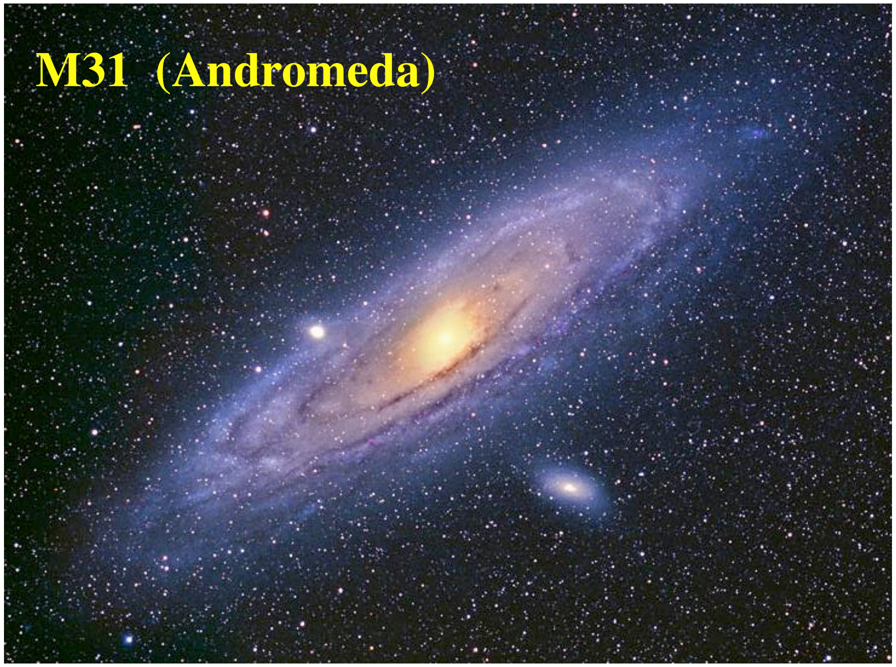
Sa **Sb** **Sc** **Sd**

Central bulge becomes less important
Disk becomes more important
Spiral arms become more open and ragged

Sb **SBb** **SBc** **SBd**

As above, except that these galaxies also have a central, linear **bar**, while the Sa, Sb… are unbarred

M31 (Andromeda)



Barred Galaxies

- Half of all disk galaxies - Milky Way included - show a central bar which contains up to 1/3 of the total light
- Bars are a form of dynamical instability in differentially rotating stellar disks
- S0 galaxies also have bars – a bar can persist in the absence of gas
- Bar patterns are not static, they rotate with a pattern speed, but unlike spiral arms they are not density waves. Stars in the bar stay in the bar
- The asymmetric gravitational forces of a disk allow gas to lose angular momentum (via shocks) compressing the gas along the edge of the bar. The gas loses energy (dissipation) and moves closer to the center of the galaxy

NGC 1300, Barred Spiral Galaxy

Dwarf Galaxies

- Low-luminosity: $10^6 - 10^{10}\ L_\odot$, low-mass: $10^7 - 10^{10}\ M_\odot$, small in size, ~ few kpc
- Often low surface brightness, so they are hard to find!
- More than one family of objects:
  - Gas-poor, passive (dE and dSph)
  - Gas-rich, star forming
- Why are dwarf galaxies important?
  - Majority of galaxies are dwarfs!
  - Dwarf galaxies may be remnants of galaxy formation process: “proto-dwarf” gas clouds came together to form larger galaxies (hierarchical formation)
  - Dwarf galaxies are currently being cannibalized by larger galaxies
  - Dwarf galaxies are relatively simple systems, not merger products: in some sense, “pristine” galaxies

LMC
dIrr

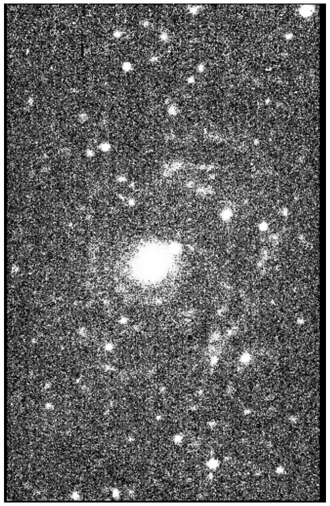
I Zw 18
Gas-rich dwarf
(very young)

Sagittarius Dwarf Spheroidal →

← NGC 205 Dwarf Elliptical

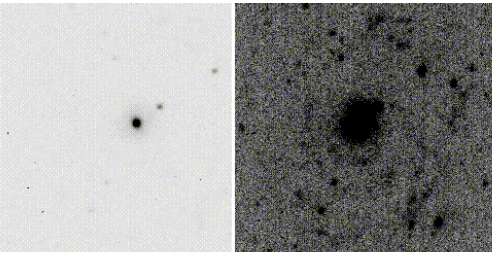
Low Surface Brightness Disks

Malin 1 - a prototype



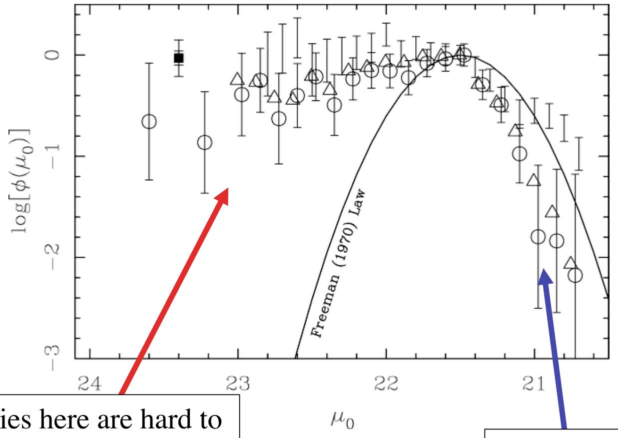
Normal size, gas, and DM content, but many fewer stars

Very hard to find, due to their diffuse nature - surveys are biased against low surface brightness objects



Surface Brightness Selection Effects

Distribution of central surface brightness for disk galaxies:

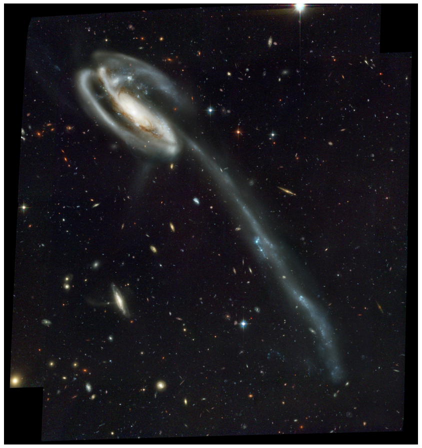


Galaxies here are hard to find, missing from most catalogs/surveys

Traditional spirals

Merging / Interacting Systems

Antennae



Tadpole

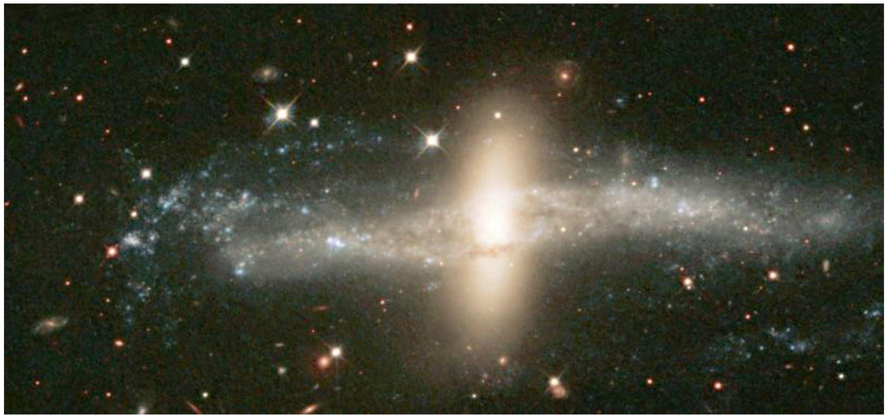
Merging / Interacting Systems

Galaxies in the process of transformation, generally from disks to ellipticals

In late stages of a merger, the 2 galaxies are no longer distinguishable, and the product does not look like any standard galaxy type

Polar Ring Galaxies

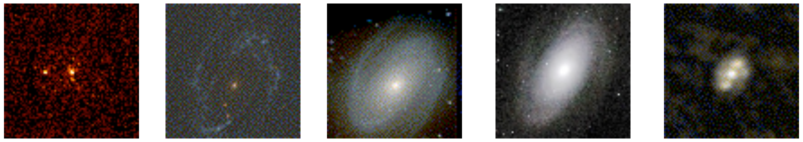
Another type of a merger-in-progress



Problems With Traditional Galaxy Classification

Appearance of galaxies is strongly dependent on **which wavelength** the observations are made in.

e.g., the nearby galaxy M81:



X-ray UV Visible Near-IR Far-IR

Note: large change in appearance between the UV and the near infrared images.

Galaxies look "clumpier" in the UV, and increasingly smooth as we go to the visible and longer wavelengths.

Problems With Traditional Galaxy Classification

Subjective - *especially for spiral galaxies*

However, there are automated, objective schemes to classify galaxies, using measured image parameters.

Superficial - *based on appearance, not physical properties*

Galaxy types or families can be defined in a parameter space of various measured/physical quantities. Different galaxy families follow different correlations.

Incomplete - *misses the major dichotomy of dwarfs and giants* (not separated in the traditional Hubble sequence)

Dwarfs also exist in gas rich / gas poor, star forming or not, and perhaps other varieties

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The Meaning of Galaxy Classification

- *Galaxy morphologies and other properties reflect different formative and evolutionary histories*
- Much can be explained by considering galaxies as composites made of two dominant visible components:
  1. Old, pressure supported bulges, where most of the star formation occurred early on
  2. Young(er), rotationally supported disks, where star formation happened gradually and is still going on
- Note that we do not involve in this the dominant mass component - the dark matter

  … and that spiral arms may be mainly ornamental …
- Nevertheless, there are some important and meaningful trends along the Hubble sequence

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Variation of Galaxy Properties Along the Hubble Sequence

	E	S0	Sa	Sb	Sc	Sd	Irr
Color	Red	→					Blue
Stellar Pop.	Old	Old + Intermediate		Old + Intermediate + Young		Intermediate + Young	
SFR	zero	low →		higher →			high
HI (gas)	Zero/ low	low →		modest →		high	highest
dust	Zero/ low	Higher		highest			Lower (less metals)
Dyn.	Bulge/halo dom.		Disk dominated, so rotation				

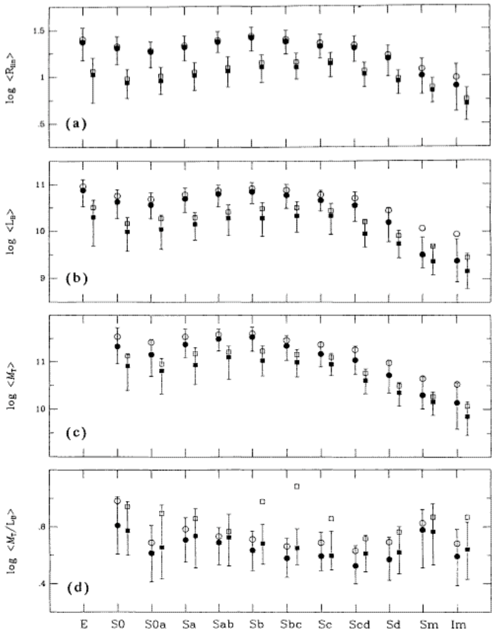
Galaxy Properties and the Hubble Sequence

Hubble sequence turned out to be surprisingly robust: many, but not all, physical properties of galaxies correlate with the classification morphology:

E S0 Sa Sb Sc Sdm/Irr →

Pressure support → Rotational support
Passive → Actively star forming
Red colors → Blue colors
Hot gas → Cold gas and dust
Old → Still forming
High luminosity density → Low lum. dens.
… etc.

But, for example, masses, luminosities, sizes, etc., do not correlate well with the Hubble type: at every type there is a large spread in these fundamental properties.



Radius

Luminosity

Mass

(M/L)

Interpreting the Trends Along the Hubble Sequence

- Probably the best interpretation of many of these is ***a trend in star formation histories:***
  - – Ellipticals and early type spirals formed most of their stars early on (used up their gas, have older/redder stars)
  - – Late type spirals have substantial on-going star-formation, didn't form as many stars early-on (and thus lots of gas left)
  - – Spirals are forming stars at a few $M_{\odot}$ per year, and we know that there is ~ a few x 10^9 $M_{\odot}$ of HI mass in a typical spiral
    - How long can spirals keep forming stars?? It seems that some gas infall/resupply is needed

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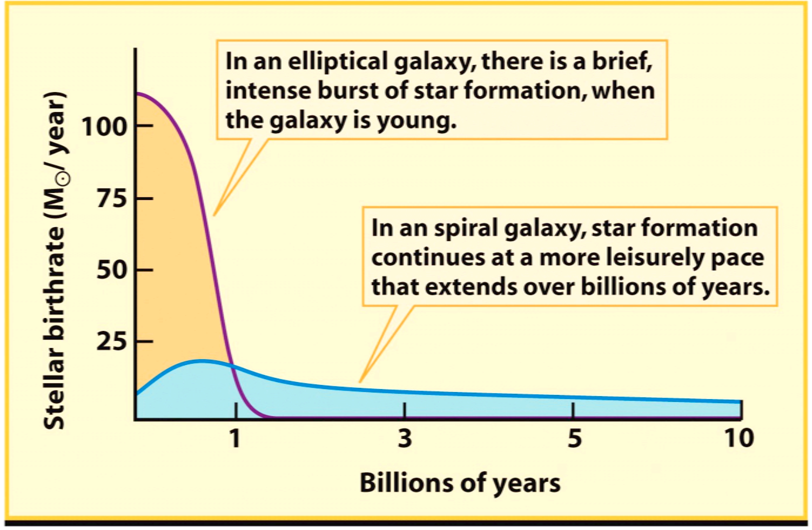
Star Formation History in Galaxies



In an elliptical galaxy, there is a brief, intense burst of star formation, when the galaxy is young.

In an spiral galaxy, star formation continues at a more leisurely pace that extends over billions of years.

The stellar birthrate in galaxies

Stellar Populations

- A key concept in our understanding of galaxies
- In 1944, Walter Baade used the 100-inch Mt. Wilson telescope to resolve the stars in several nearby galaxies: M31, its companions M32 and NGC 205, as well as the elliptical galaxies NGC 147 and NGC 145
- Realized the stellar populations of spiral and elliptical galaxies were distinct:
  - **Population I:** objects closely associated with spiral arms – luminous, young hot stars (O and B), Cepheid variables, dust lanes, HII regions, open clusters, metal-rich
  - **Population II:** objects found in spheroidal components of galaxies (bulge of spiral galaxies, ellipticals) – older, redder stars (red giants), metal-poor

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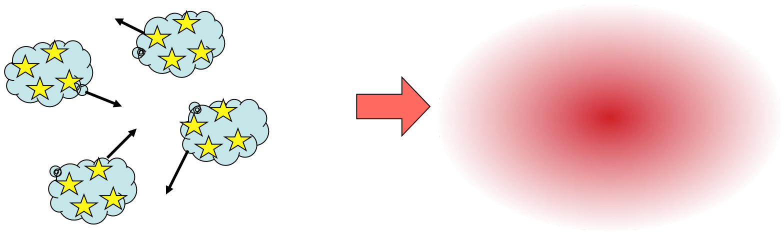
Stellar Populations and Dynamical Subsystems in Galaxies

- The picture today is more complex: it is useful to thing about generalized stellar populations as subsystems within galaxies, characterized by the:
  - Location and morphology, density distribution
  - Dynamics (rotation, random motions, their distribution)
  - Star formation rate and mean age
  - The presence and nature of its interstellar medium

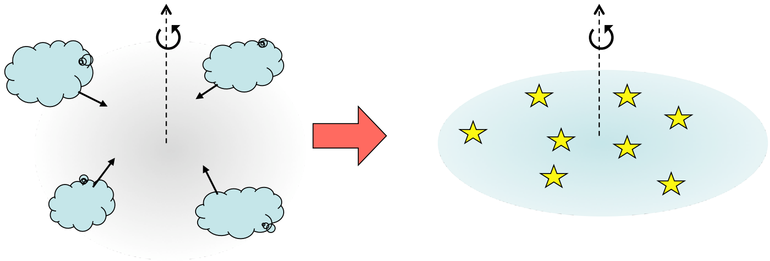
  etc., etc.
- For example, in the Milky Way, we can distinguish:
  - Young thin disk
  - Old thick disk
  - Metal-rich bulge (and bar?)
  - Metal-poor stellar halo

Formation of Galaxy Spheroids and Dynamics of Stellar Populations



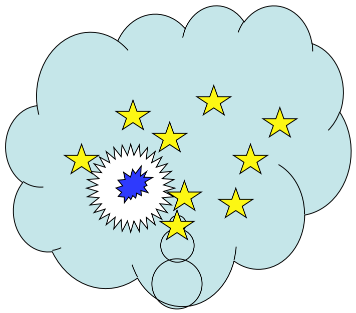
Stars "remember" the dynamics of their orbits at the time of formation, since dynamics of stellar systems is dissipationless. If stars form in dwarf protogalactic fragments which then merge, this will result in a pressure-supported system, *i.e.*, a spheroid (bulge or halo, or an elliptical galaxy). Their metallicities will reflect the abundances in their parent systems.

Formation of Galaxy Disks and Dynamics of Stellar Populations

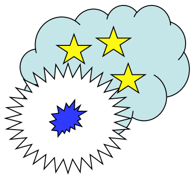


If protogalactic clouds merge dissipatively in a potential well of a dark halo, they will settle in a thin, rotating disk = the minimum energy configuration for a given angular momentum. If gas settles into a (dynamically cold) disk before stars form, then stars formed in that disk will inherit the motions of the gas (mainly an ordered rotation).

Chemical Self-Enrichment in Young Stellar Systems

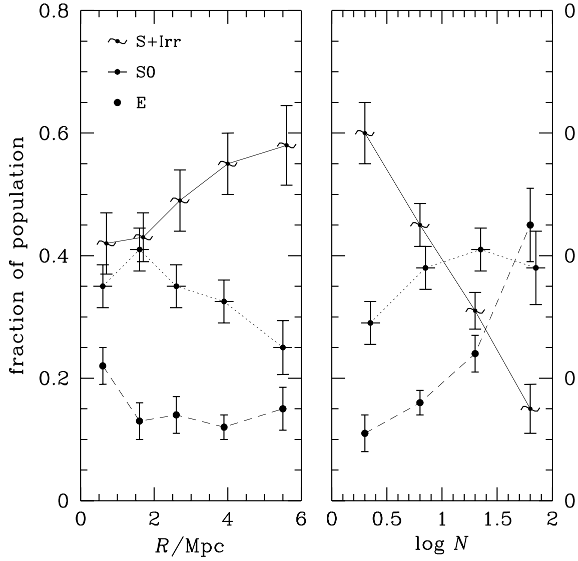


In a massive system, supernova ejecta are retained, and reused for subsequent generations of stars, which achieve ever higher metallicities.



In a low-mass system, supernova shocks and star winds from massive young stars expell the enriched gas and may supress any subsequent star formation. The system retains its initial (low) metallicity.

Morphology-Density Relation



Binney & Merrifield, Galactic Astronomy

Galaxy Luminosity and Mass Functions

- We'd really like to have a ***galaxy mass function*** - distribution of galaxy masses - but masses are hard to measure, so we settle for the ***luminosity function*** (LF)
- Count the number of galaxies as a function of luminosity (or absolute magnitude) - a basic descriptor of the galaxy population
- Useful for:
  - Understanding galaxy formation (distribution by luminosity implies distribution by mass – how many galaxies of a given type and mass were formed)
  - Galaxy evolution models – either must reproduce observed LFs (hierarchal formation models) or assume them (and work backwards in time). Can also measure evolution in LFs vs. redshift!

The Galaxy Luminosity Function

The luminosities of galaxies span a very wide range - most luminous ellipticals are 10^7 more luminous than faintest dwarfs

Luminosity function, $\phi(L)$, describes the relative number of galaxies of different luminosities. The formal definition:

If we count galaxies in a representative volume of the universe, $\phi(L)\,dL$ is the number of galaxies with luminosities between L and $L + dL$

(… and the equivalent for the galaxy mass function)

Luminosity functions are easiest to measure in clusters of galaxies, where all the galaxies have the same distance, but clusters may not be representative of the general field

The Schecter Luminosity Function

A convenient approximation to the luminosity function was suggested by P. Schecter in 1976:

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

where:

- $\boldsymbol{n_*}$ (sometimes $\boldsymbol{\phi_*}$ is used) is a normalization factor which defines the overall density of galaxies (number per Mpc^3)
- $\boldsymbol{L_*}$ is a characteristic galaxy luminosity. An L_* galaxy is a bright galaxy, roughly comparable in luminosity to the Milky Way. A galaxy with $L < 0.1\ L_*$ is a dwarf
- $\boldsymbol{\alpha}$ defines the faint-end slope of the luminosity function; it is typically negative, implying large numbers of galaxies with low luminosities

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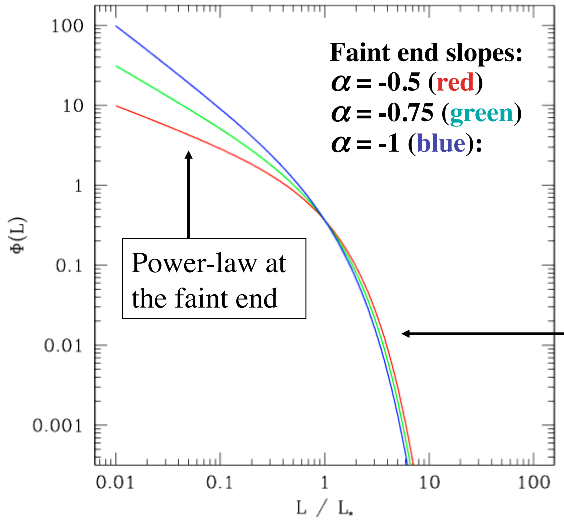
The Schecter Luminosity Function



Faint end slopes:
α = -0.5 (red)
α = -0.75 (green)
α = -1 (blue):

Power-law at the faint end

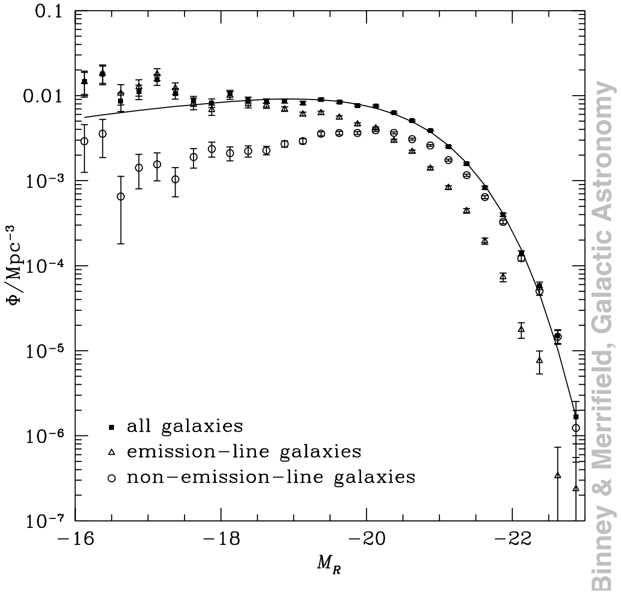
Exponential cutoff at the bright end

Typical parameters:

$\phi_* \sim 0.01$ Mpc^{-3}

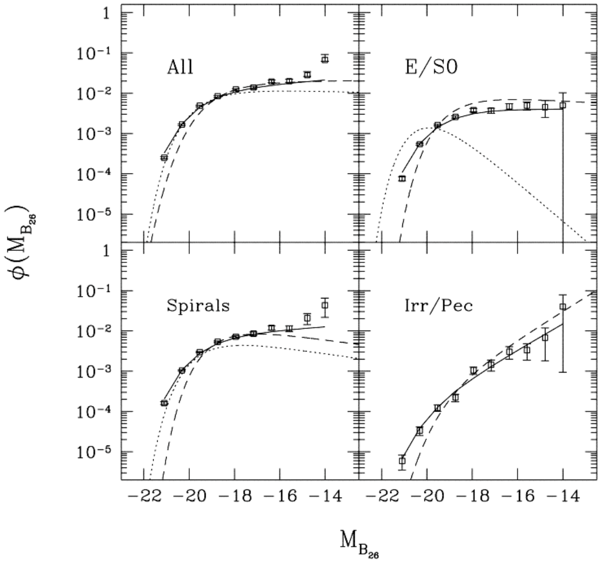
$L_* \sim 10^{10}\ L_\odot$

Luminosity Function From LCRS



Binney & Merrifield, Galactic Astronomy

GLF: Morphological Type Dependence

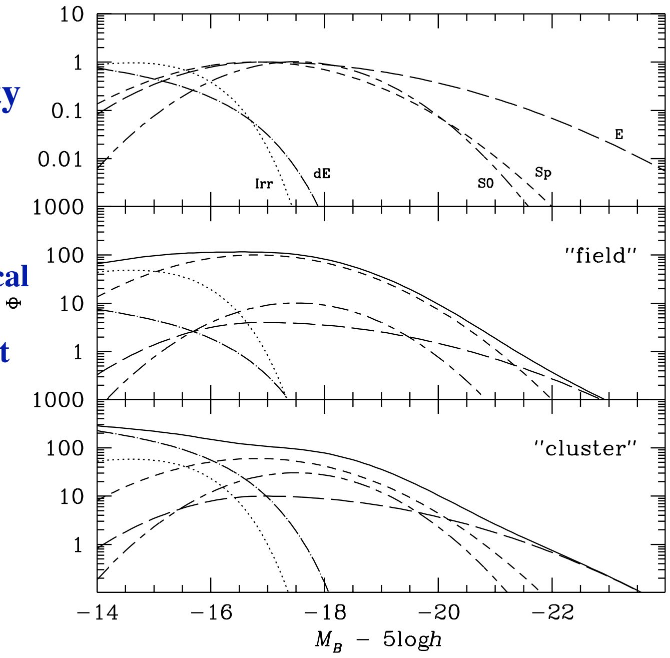


The faint end is dominated by the dwarf galaxies (here dIrr are shown, but dE are also numerous)

Marzke (1998)

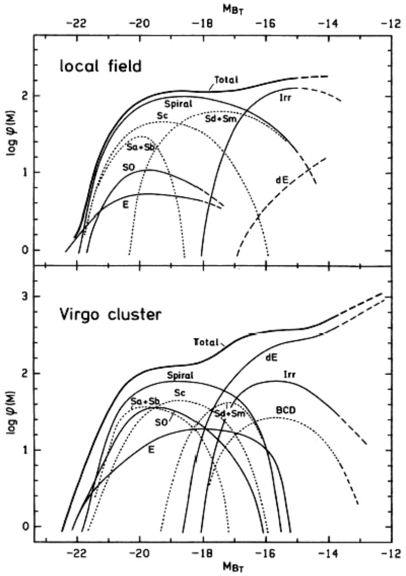
Galaxy Luminosity Function:

Morphological Type and Environment Dependence



Binney & Merrifield, Galactic Astronomy

LF Mix in Different Environments



Field: dominated by spirals, faint end by dIrr

Clusters: many more E/S0 galaxies, faint end dominated by dE, more dwarfs than in field

Note that the LF's of the classical Hubble types are nearly log-normal, i.e., have a cutoff at the faint end. The faint end power-law is completely dominated by dwarfs!

Bingelli (1988)

Integrating the Schecter GLF

The total number of galaxies per unit volume with luminosity greater than L is:

$$n = \int_L^\infty \Phi(L)\,dL$$

This integral is not expressible in terms of elementary functions :-(

If $\alpha < -1$, n diverges as L tends toward zero. This is clearly unphysical, so Schecter LF must fail for very low luminosity galaxies (or have a larger α)

The luminosity density (units = Solar luminosities per Mpc^3) is given by:

$$\int_L^\infty \Phi(L)\,L\,dL \quad \sim \text{a few } \times 10^8\ L_\odot\ \text{Mpc}^{-3}$$

Dominated by galaxies with $L \sim L_*$ for typical value of α

Significance of the Schecter Function

Does the Schecter form of the GLF have any deeper physical significance - or is it just a good fitting function?

- Luminous galaxies become exponentially rarer at high enough luminosities. Similar to a general result in cosmology (confusingly, *Press-Schecter* theory) - the number density of massive objects (e.g. clusters) drops off exponentially at high masses.

- But remember that Schecter function is a composite which includes **all types of galaxies**. Luminosity function of any individual class of galaxies looks very different - and none look like the Schecter LF

Mass Function of Galaxies

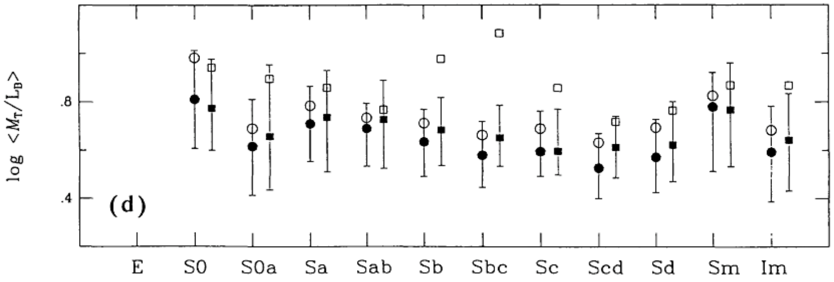
For stars, measurements of the luminosity function can be used to derive the Initial Mass Function (IMF). For galaxies, this is more difficult:

- Mass to light ratio (M/L) of the **stellar** population depends upon the star formation history of the galaxy
- Image of the galaxy tells us nothing about the amount and distribution of the dark matter
- Thus, more difficult kinematical measurements and dynamical modeling are needed, for a broad range of galaxies; this is especially hard at the faint end

… Yet, mass function is what theoretical models predict, so comparing them with observations is a very tricky business!

Mass to Light (M/L) Ratios

Typical (*M*/*L*) ratios in the *B* band along the Hubble sequence, within the luminous portions of galaxies, are ~ 4 - 5 $M_\odot/L_\odot$



This includes some dark matter - for pure stellar populations, (*M*/*L*) ratios should be slightly lower.
Note that in the *B* band, they are very sensitive to any recent star formation, and to dust extinction.

Quantifying Properties of Galaxies

For galaxies of different types, we would like to quantify:

- The distribution of light - need photometric measurements
- The distribution of mass - need kinematical measurements
- Relative distributions and interplay of various components, e.g., stars, gas, dark matter - need multiwavelength measurements, as different components tend to emit most energy in different wavebands, e.g., stars → visible/near-IR, cold gas → radio, dust → far-IR, hot gas → x-rays, etc.
- Chemical composition, star formation rates - need spectroscopy

All these measurements can then be analyzed using:

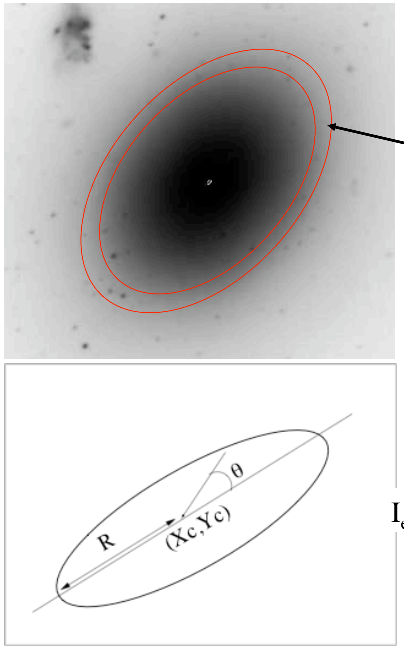
- Dynamical models
- Stellar population synthesis models
- Galaxy evolution models

Note: we tend to measure different observables for different galaxy types!

Surface Photometry

- The way to quantify the 2-dimensional distribution of light, e.g., in galaxies
- Many references, e.g.,
  - Davis et al., AJ, 90, 1985
  - Jedrzejewski, MNRAS, 226, 747, 1987
- Could fit (or find) ***isophotes***, and the most common procedure is to fit elliptical isophotes.
- Isophotal parameters are: surface brightness itself (μ), x_{center}, y_{center}, ellipticity (ε), position angle (PA), the enclosed magnitude (m), and sometimes higher order shape terms, all as functions of radius (r) or semi-major axis (a).

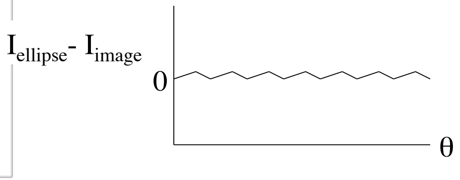
Isophote Fitting



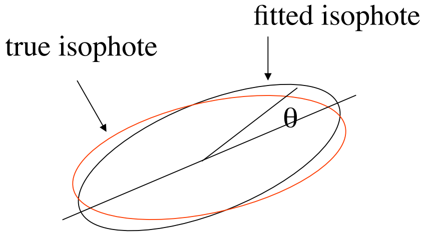
Calculate mean and RMS pixel intensity for annulus, toss any values above mean + n × RMS

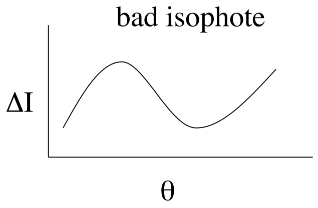
Start with guesses for x_c, y_c, R, ε and p.a., then compare the ellipse with real data all along the ellipse (all θ values)

Good isophote:



Isophote Fitting





Fit the ΔI - θ plot and iterate on x_c, y_c, p.a., and ε to minimize the coefficients in an expression like:

$$I(\theta) = I_0 + A_1\sin(\theta) + B_1\cos(\theta) + A_2\sin(2\theta) + B_2\cos(2\theta)$$

Changes to x_c and y_c mostly affect A_1, B_1,
p.a. " " A_2
ε " " B_2

More specifically, iterate the following:

$$\Delta(\text{major axis center}) = \frac{-B_1}{I'}$$

$$\Delta(\text{minor axis center}) = \frac{-A_1(1-\varepsilon)}{I'}$$

$$\Delta(\varepsilon) = \frac{-2B_2(1-\varepsilon)}{a_0 I'}$$

$$\Delta(\text{p.a}) = \frac{2A_2(1-\varepsilon)}{a_0 I'[(1-\varepsilon)^2 - 1]}$$

where :

$$I' = \left.\frac{\partial I}{\partial R}\right|_{a_0}$$

- After finding the best-fitting elliptical isophotes, the residuals are often interesting. Fit:

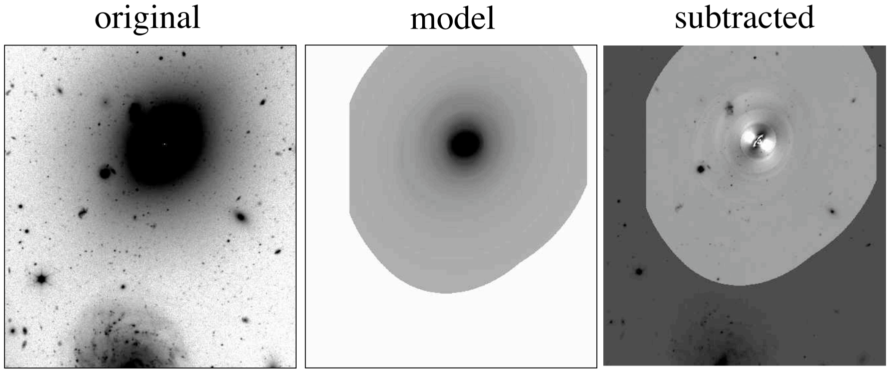
  $$I = I_0 + A_n\sin(n\theta) + B_n\cos(n\theta)$$

  already minimized n=1 and n=2, n=3 is usually not significant, but:

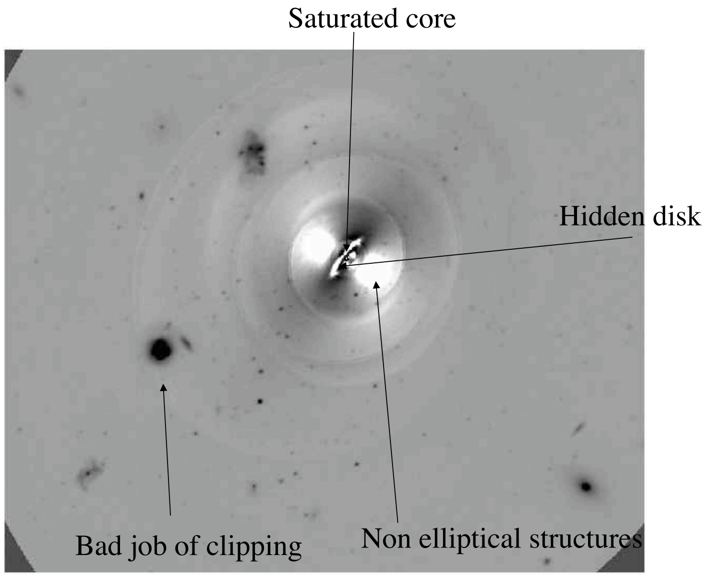
  B_4 is negative for "boxy" isophotes

  B_4 positive for "disky" isophotes

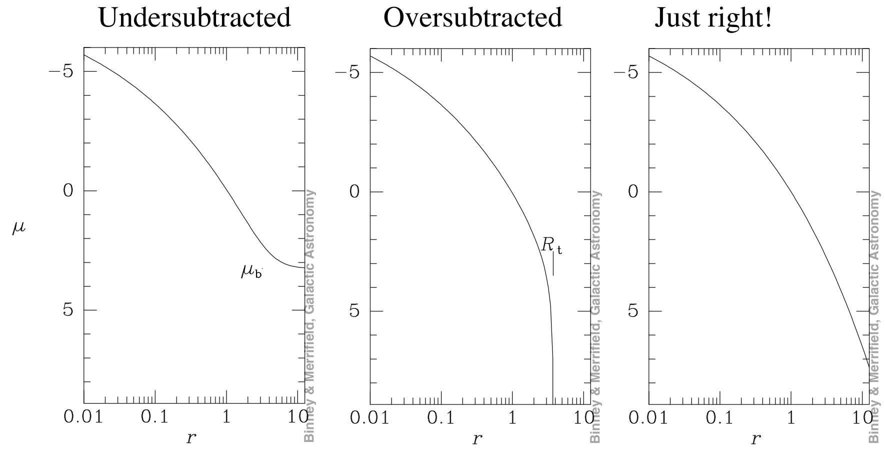
From your isophotal fits, you can then construct the best 2-dimensional elliptical model for the light distribution



… and subtract it from the image to reveal any deviations from the assumed elliptical symmetry



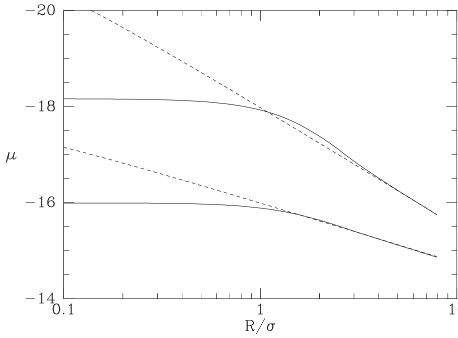
The Effects of Sky Subtraction


Undersubtracted

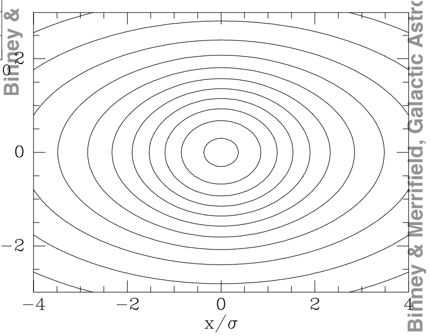
Oversubtracted

Just right!

The Effects of Seeing



Flattening of the
central cusps
(false cores)



Rounding of the
inner isophotes

Photometric Properties of Galaxies

Empirically, the surface brightness declines with distance from the center of the galaxy in a characteristic way for spiral and elliptical galaxies

For spiral galaxies, need first to correct for:

- Inclination of the disk
- Dust obscuration
- Average over spiral arms to obtain a mean profile

Corrected disk surface brightness drops off as:

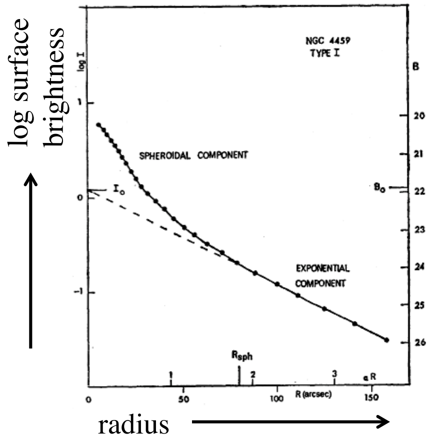
$$I(R) = I(0)\ e^{-R/h_R}$$

where ***I(0)*** is the central surface brightness of the disk, with a broad range of values, but typically ~ 21 - 22 mag/arcsec^2, and $\boldsymbol{h_R}$ is a characteristic **scale length**, with typical values:

$$1\ \text{kpc} < h_R < 10\ \text{kpc}$$

Bulge-Disk Decomposition

In practice, surface brightness at the center of many spiral galaxies is dominated by stars in a central bulge. Central surface brightness of disk must be estimated by extrapolating inward from larger radii



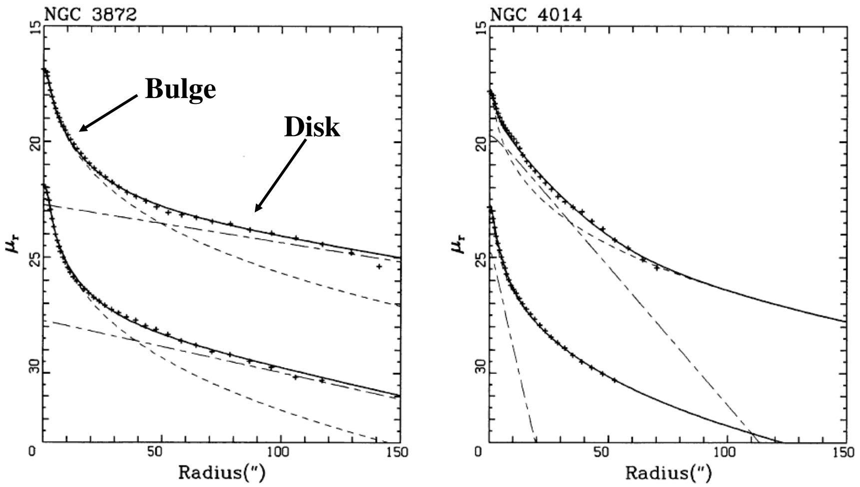
Component profiles (μ is the logarithmic surface brightness in mags/arcsec2):

$$\mu_{\text{bulge}} = \mu_e + 8.325\left[\left(r/r_e\right)^{1/4} - 1\right]$$

$$\mu_{\text{disk}} = \mu_0 + 1.082\left(r/h\right).$$

Radial Surface Brightness Profiles of Spiral Galaxies

Note: semi-log profiles



(from S. Kent)

Elliptical Galaxies: Surface Photometry

Surface brightness of elliptical galaxies falls off smoothly with radius. Measured (for example) along the major axis of the galaxy, the profile is normally well represented by the $R^{1/4}$ or de Vaucouleurs law:

$$I(R) = I(0)\ e^{-kR^{1/4}}$$

where k is a constant. This can be rewritten as:

$$I(R) = I_e\ e^{\left\{-7.67\left[\left(R/R_e\right)^{0.25} - 1\right]\right\}}$$

where R_e is the **effective radius** - the radius of the isophote containing half of the total luminosity. I_e is the surface brightness at the effective radius. Typically, the effective radius of an elliptical galaxy is a few kpc.

De Vaucouleurs' Law

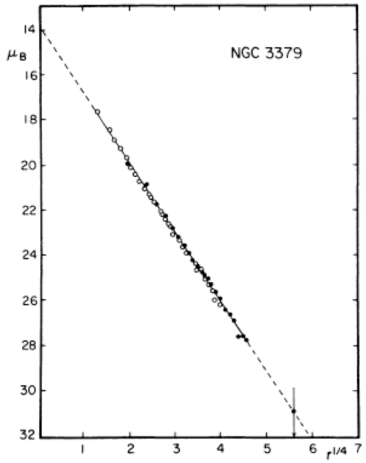
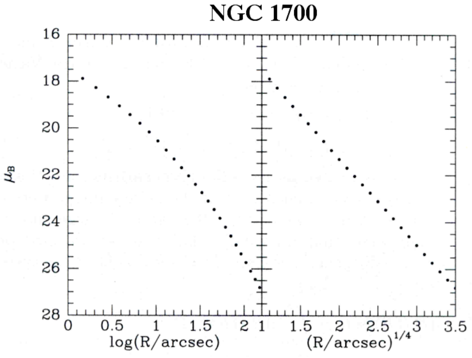


FIG. 2.—Mean E-W luminosity profile of NGC 3379 derived from McDonald photoelectric data. ●, Pe 4 data with 90 cm reflector; ○, Pe 1 data (M + P) with 2 m reflector. Note close agreement with $r^{1/4}$ law.



$R^{1/4}$ profile fits the data very well over some 2 decades in radius

Other Common Profiles

Sersic profile:

$$\Sigma(r) = \Sigma_0 \exp\left\{-b_n \left[(r/r_e)^{1/n}\right]\right\}$$

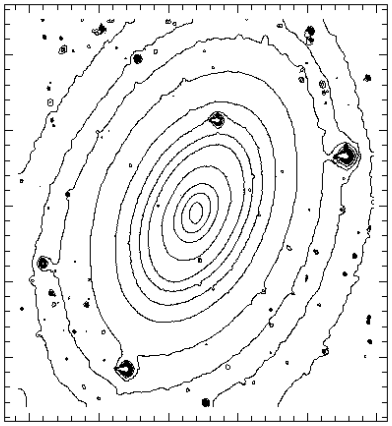
where $\boldsymbol{\Sigma}$ is the surface brightness in linear units (not magnitudes), $\mathbf{b_n}$ is chosen such that half the luminosity comes from $R < R_e$. This law becomes de Vaucouleurs for $n = 4$, and exponential for $n = 1$.

Hubble's profile:

$$\Sigma(r) = \frac{\Sigma_s}{(1+\frac{r}{r_s})^2}$$

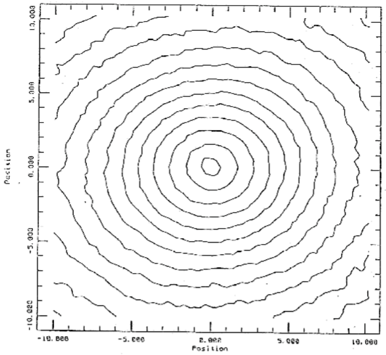
with Σ_0 the central surface brightness, and r_0 the "core" radius interior to which the surface brightness profile is approx. constant. Note that the integral under the Hubble profile diverges!

Typical Elliptical Isophotes



NGC 1533

Note the apparent ellipticity gradient

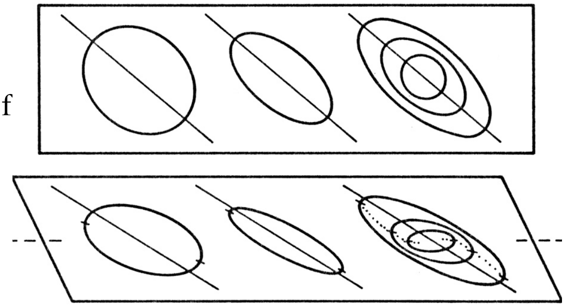


NGC 4689

Isophote Twisting

Generally speaking, galaxies can be ***triaxial ellipsoids***

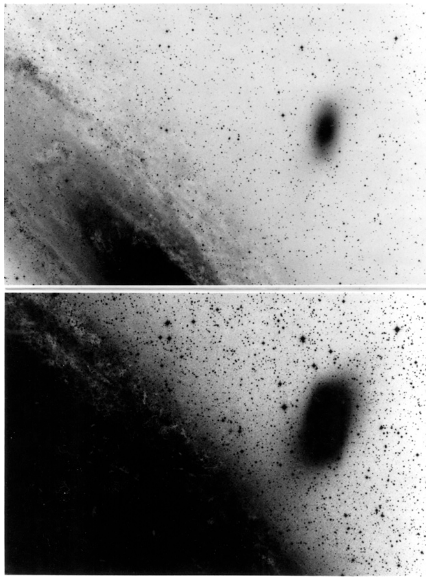
In a triaxial case, the orientation in the sky of the projected ellipses will not only depend upon the orientation of the body, but also upon the body's axis ratio. This is best seen in the projection of the following 2-D figure:



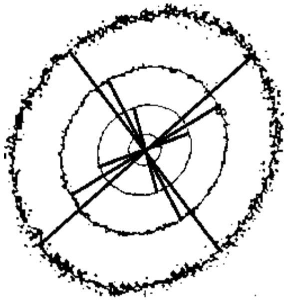
Since the ellipticity changes with radius, even if the major axis of all the ellipses have the same orientation, they appear as if they were rotated in the projected image. This is called ***isophote twisting***.

Isophote Twists

Here is an example of twisted isophotes in a satellite galaxy of Andromeda (M31):

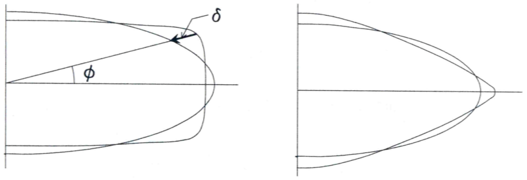


And another:



Isophotes: Deviations From Ellipses

Isophotes are not perfect ellipses. There may be an excess of light on the major axis (disky), or on the “corners” of the ellipse (boxy):



The ***diskiness/boxiness*** of an isophote is measured by the difference between the real isophote and the best-fit elliptical one:

$$\delta(\phi) = \langle\delta\rangle + \Sigma\, a_n \cos n\phi + \Sigma\, b_n \sin n\phi$$

where the terms with n < 4 all vanish (by construction), and $a_4 > 0$ is a disky E, while $a_4 < 0$ corresponds to a boxy E.

Disky and Boxy Elliptical Isophotes

FIGURE 3. — Distribution of the ellipticity classes for all observed elliptical galaxies.

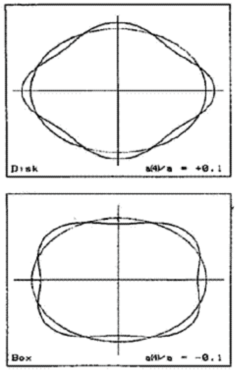


FIGURE 5. — Schematic drawing illustrating isophotes with $a(4)/a = +0.1$ and $a(4)/a = -0.1$.

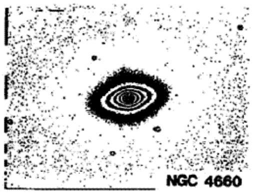


FIGURE 6. — R-image of NGC 4660, an elliptical galaxy with a disk-component in the isophotes ($a(4)/a \sim +0.03$).

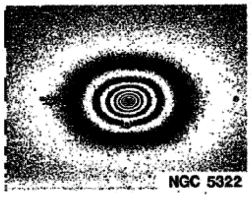
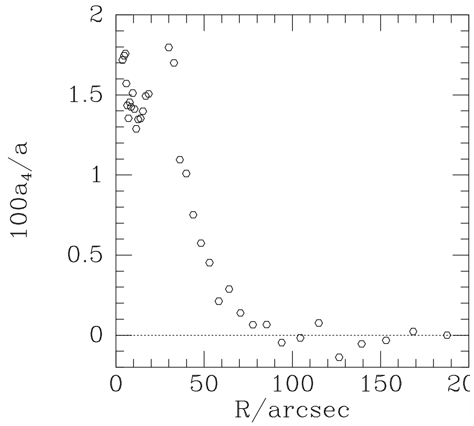
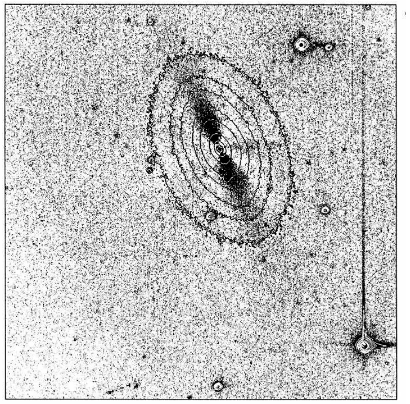


FIGURE 7. — R-image of NGC 5322, an elliptical galaxy with box-shaped isophotes ($a(4)/a \sim -0.01$).

Examples for boxy and disky isophotes from Bender et al. (1988)

An Example of a Disky Elliptical

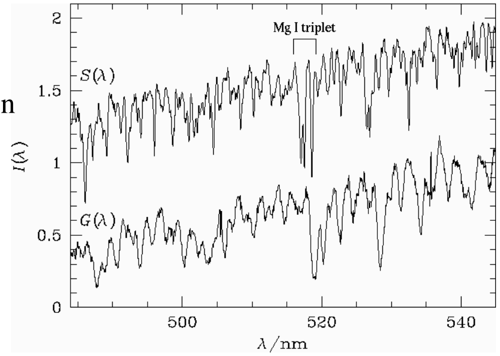




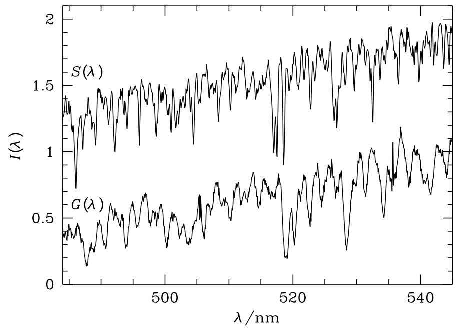
The Kinematics of E-Galaxies

Stars in E galaxies have some ordered motions (e.g., rotation), but most of their kinetic energy is in the form of random motions. Thus, we say that ellipticals are ***pressure-supported systems***

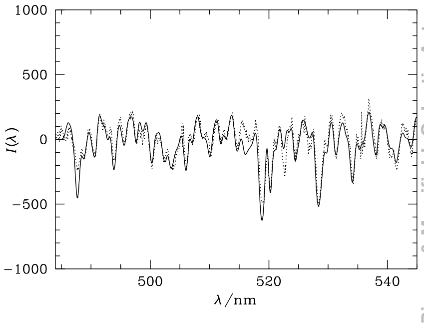
To measure the kinematics within galaxies we use absorption lines. Each star emits a spectrum which is Doppler shifted in wavelength according to its motion. Random distribution of velocities then broadens the spectral lines relative to those of an individual star. Systemic motions (rotation) shift the line centroids.



The Cross-Correlation Technique



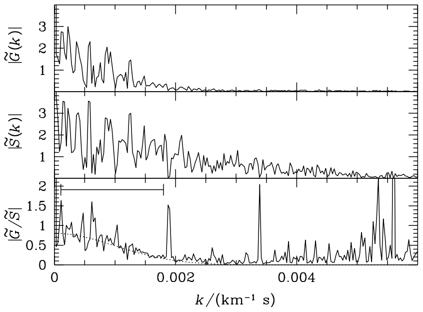
Stellar spectrum template S(λ), and galaxy spectrum, G(λ), modelled as a convolution of S(λ) with a velocity dispersion function V(λ), usually assumed to be a Gaussian.

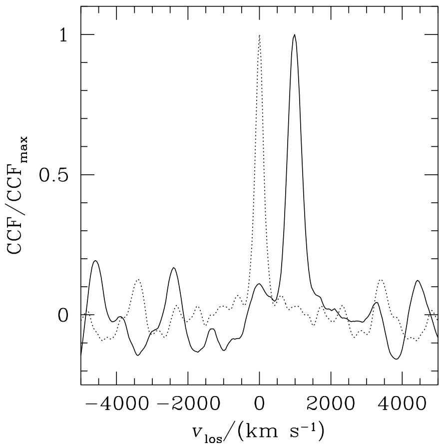


Fit the convolved template spectrum S(λ)*V(λ) to the observed galaxy spectrum, G(λ), for a range of velocity dispersions σ (broadening).

The Cross-Correlation Technique

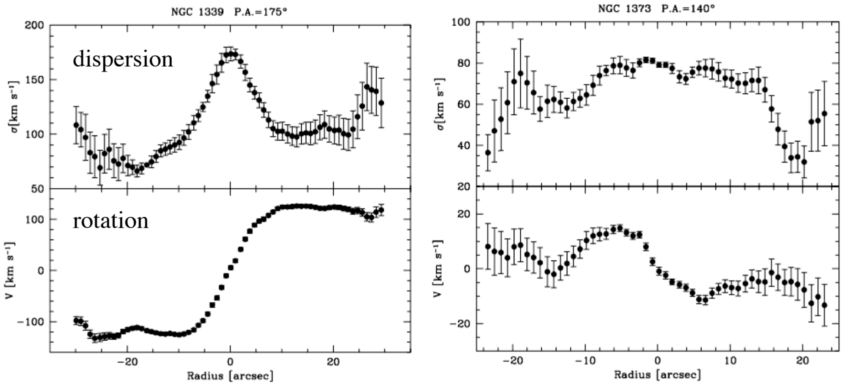
To measure redshifts, cross-correlate S(λ) and G(λ), binned to log λ axis, to determine the shift in Δλ/λ = *v*/*c*





Need a good template match…

Kinematical Profiles of E-Galaxies



- Rotation is present, but generally not a dominant component of the kinetic energy
- Velocity dispersion tends to be higher closer to the center

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2-Dimensional Kinematics of E-Gal's