Part I
Introduction to Galaxies

Overview

- Galaxies are a major building block of the Universe.
- Basic nature of galaxies – "Island Universes" – not confirmed until the 1930's.
- Galaxies are complex, multi-component entities, and aspects of their formation and subsequent evolution are poorly understood.
- Observing the epoch of first galaxy formation is a major theme in cosmology.
- Galaxies are often found in groups and clusters of galaxies.
- Galaxies continually interact with their environments – outflows, inflows, galaxy mergers, cannibalism etc.
- The characteristics of galaxies depend on their environment – different sorts of galaxies are preferentially found in dense or diffuse regions.

The Components of Galaxies

Three main components:

- Stars – generations of star-formation, evolution and stellar death.
- Interstellar medium (gas/dust) – both cold and hot gas, including extended galaxy halos.
- Dark matter.

These three very different kinds of things all interact with each other (gravity, star-birth, star-death).
Interaction with other galaxies and the local environment crucially affects the evolution of galaxies.
Some galaxies (more of them in earlier epochs) have 'active nuclei' which can vastly outshine the starlight.
Probably all galaxies have large black holes at the centre (perhaps except those that are tiny).

The Lives of Stars

Normal stars have a range of masses from $\sim 0.1 M_\odot$ up to $\sim 200 M_\odot$.
Range of temperatures: < 3000 K up to > 50000 K.

Spectral types: OBAFGKM: O-type stars to M-stars.

Spectral classes: I, II, III, IV, V - supergiants to main sequence stars.

Examples: Sun: G2 V, Sirius: A1 V, Rigel: B8 I, Betelgeuse: M2 I

For main-sequence (MS) stars, we have rough expressions for stellar radius (R_*) and luminosity (L_*) in terms of their stellar mass (M_*) :

$$R_*(R_\odot) = \left(\frac{M_*}{M_\odot}\right)^{0.7} \qquad L_*(L_\odot) = \left(\frac{M_*}{M_\odot}\right)^{\alpha} \tag{1.1}$$

with

$\alpha = 5$ for $M < M_\odot$
$\alpha = 3.9$ for $M_\odot < M < 10M_\odot$

For higher mass stars (with $M > 10M_\odot$):

$$L(L_\odot) = 50\left(\frac{M}{M_\odot}\right)^{2.2} . \tag{1.2}$$

Main Sequence Time-scales

Stars spend most of their lives on the main-sequence.

The main sequence lifetime (τ_{MS}) can be expressed roughly as follows:

$$\tau_{MS}(\tau_{MS,\odot}) = \left(\frac{M/L}{M_\odot/L_\odot}\right) \rightarrow \tau_{MS} = 10\,\mathrm{Gyr}\left(\frac{M}{M_\odot}\right)^{-2.5} = 10\,\mathrm{Gyr}\left(\frac{L}{L_\odot}\right)^{-5/7} . \tag{1.3}$$

Here, $\tau_{MS,\odot}$ is the main-sequence lifetime of the Sun (around 10 Gyr) and we have assumed $\alpha \sim 3.5$.

The Big Bang occurred $\sim$ 14 Gyr ago and as a consequence no stars with $M < 0.8M_\odot$ have yet to leave the main-sequence.

A lot of the stellar mass of galaxies is locked up in these low-mass, but long-lived stars.

Stellar Evolution

- Very Low Mass Stars ($M < 0.6M_\odot$): Still on main sequence – hydrogen burning.
- Low Mass Stars ($0.6M_\odot < M < 2M_\odot$): H burning on MS $\rightarrow$ core H exhaustion (subgiant) $\rightarrow$ shell H burning (red giant) $\rightarrow$ core He burning (red clump stars) $\rightarrow$ shell He and H burning (Asymptotic Giant Branch star) $\rightarrow$ planetary nebula and white dwarf
- Intermediate masses ($2M_\odot < M < 8M_\odot$): similar history but become Cepheid variables when He burning.
- Massive Stars ($10M_\odot < M < 40M_\odot$): in addition to He burning, the core become hot enough to support C and O burning. Eventual explosion as a Type II supernova, resulting in a neutron star.
- Very massive Stars ($M > 40M_\odot$): Evolution dominated by mass-loss in a stellar wind $\rightarrow$ Wolf-Rayet stars. Explosion as Type II (or Type Ib/Ic SN) and resulting black-hole or no remnant (connection with gamma-ray bursts too).

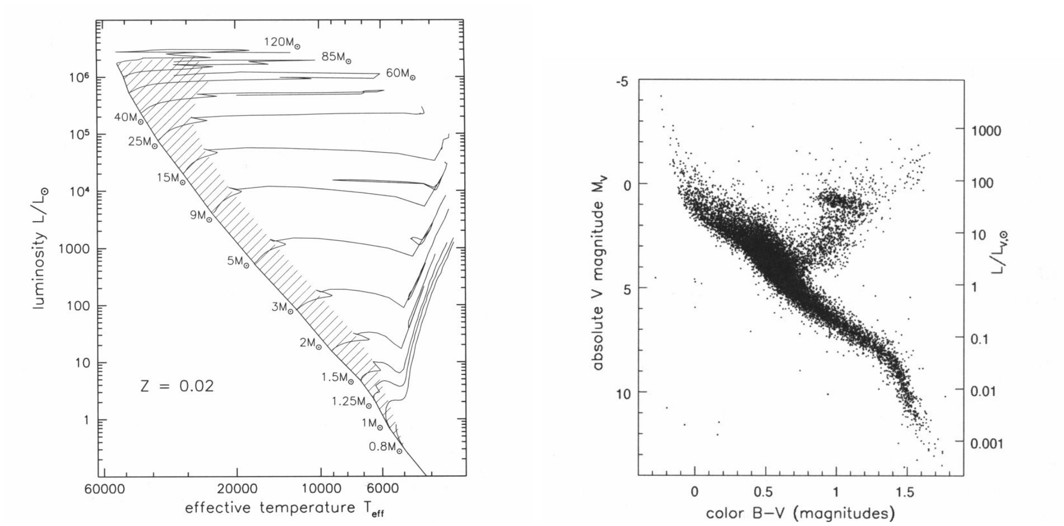

Figure 1.1: Left: The theoretical Hertzsprung-Russell (H-R) diagram, showing the evolutionary tracks of stars of different initial ZAMS (zero-age main sequence) masses. The hatched region shows where the stars are core-burning hydrogen. Right: The observational H-R diagram for stars near the Sun. Here the colour of the star $(B-V)$ acts as a proxy for temperature. The main-sequence is clearly visible as are the red giants.

Stellar Initial Mass Function (IMF)

$\xi(M)dM$ is the number of stars that are born with a mass in the range of M to $M+\delta M$ and is often represented by the Salpeter Initial Mass Function (IMF), with

$$\xi(M) = \xi_0 M^{-2.35} \tag{1.4}$$

This relationship implies that there are a lot more low-mass stars than high mass stars.

Stellar Luminosity Function

The stellar luminosity function is essentially the mass function weighted by the luminosity of the stars.

Because massive stars are so much more luminous than low-mass stars they can dominate the light from the galaxy.

Mass-Luminosity (M/L) Ratios

We often express the mass-luminosity ratio of regions in terms of the stellar values.

The Sun has a M/L ratio of 1 (in units of $M_\odot/L_\odot$).

Regions with lots of young, high mass stars have low M/L ratios and vice versa.

We can also work out the M/L ratios for whole galaxies – often have a lot of unseen (dark) matter and hence higher ratios.

Dynamical Timescales

Consider an isolated star cluster (for example 47 Tucanae):
N – number of stars in cluster
m – mass of each star
R – cluster radius (or characteristic size scale). v: the average speed of the stars with respect to the centroid of the cluster.

Assume average separation between two stars is roughly the radius R of the system.

The **Virial theorem** states that for any system bound by an inverse square force, the time-averaged kinetic energy $\langle T\rangle$ and the time-averaged potential energy $\langle V\rangle$ satisfy:

$$2\langle T\rangle + \langle V\rangle = 0. \tag{1.5}$$

This implies that

$$2 \times \frac{1}{2} N m v^2 \approx \frac{G(Nm)^2}{R}, \tag{1.6}$$

which leads to a characteristic velocity for the system of

$$v^2 \sim \frac{GNm}{R}. \tag{1.7}$$

Crossing Time

The time taken by a star, moving with the characteristic velocity, to move the characteristic size scale of the system. This provides a useful timescale:

$$T_{\text{cross}} = \frac{R}{v} \approx \left(\frac{R^3}{GNm}\right)^{1/2}. \tag{1.8}$$

This is also known as the *dynamical timescale* of the system.

Examples: Crossing times for systems of stars and galaxies

Globular cluster:

Assume $N = 10^6$ stars, $R = 10$ pc and a mean stellar mass of $m = 0.5 M_\odot$.

The crossing time turns out to be $T_{\text{cross}} = 0.7 \times 10^6$ yr (0.7 Myr).

Core of a galaxy cluster:

Assume $v = 500\,\text{km s}^{-1}$, $R = 2$ Mpc.

The crossing time is $T_{\text{cross}} = R/v = 4 \times 10^9$ yr $= 4$ Gyr.

Conclusions: Globular clusters are well mixed, whereas clusters of galaxies are necessarily not so.

Stellar Close Encounters

Imagine that each star has a "sphere of influence" of radius r_s around its centre.

Call an event an "encounter" if the centres of two stars came closer to each other than r_s.

Define *strong* encounters to occur when two stars come close enough such that their mutual gravitational potential energy is of the same order as their kinetic energy, $\frac{1}{2}mv^2 \approx Gm^2/r_s$, which implies that their separation

$$r < r_s = \frac{2Gm}{v^2}. \tag{1.9}$$

For the solar neighbourhood, where $v = 30\ \text{km s}^{-1}$, $r_s \sim 2$ AU.

If the local density of stars is n, and a typical random speed v, then the cylindrical volume swept out by a single star's sphere of influence in a time T_s is $\pi r_s^2 v T_s$.

This volume can contain just one other star (if it had more, then in the same time interval there would have been more collisions).

Therefore,

$$n(\pi r_s^2 v T_s) = 1 \tag{1.10}$$

or,

$$T_s = \frac{1}{n\pi r_s^2 v} = \frac{v^3}{4\pi G^2 m^2 n} \sim 4 \times 10^{12}\ \text{yr} \left(\frac{v}{10\ \text{km s}^{-1}}\right)^3 \left(\frac{m}{M_\odot}\right)^{-2} \left(\frac{n}{1\ \text{pc}^{-3}}\right)^{-1}, \tag{1.11}$$

Solar neighbourhood – $v = 30\ \text{km s}^{-1}$, $n = 0.1\ \text{pc}^{-3}$ and $m = 0.5M_\odot$, implies $T_s \sim 5 \times 10^{15}$ yr.

To calculate the frequency of actual "collisions", substitute r_s by the radius of a star ($R_\odot = 7 \times 10^8$ m).

Obvious that collisions between stars are *very* infrequent – $T_{\text{collision}} \sim 10^{20}$ yr.

Not necessarily so in cores of dense star clusters – particularly 3-body interactions (star+binary system).

But what about the cumulative effect of all the stars in the system?

Relaxation Time

The two-body relaxation time T_{relax} is the time taken for a star's velocity to be changed significantly from two-body interactions, such that $\Delta v^2 \sim v^2$.

This means that the memory of the stars initial motion has been lost.

Most textbooks (e.g. Sparke & Gallagher §3.2.2) have a derivation for T_{relax}:

$$T_{relax} = \frac{v^3}{8\pi (Gm)^2 n \ln\Lambda} = \frac{T_s}{2\ln\Lambda} \sim \frac{2 \times 10^9\ \text{yr}}{\ln\Lambda} \left(\frac{v}{10\ \text{km s}^{-1}}\right)^3 \left(\frac{m}{M_\odot}\right)^{-2} \left(\frac{n}{1\ \text{pc}^{-3}}\right)^{-1}, \tag{1.12}$$

with $\Lambda = N/2$, where

n – the stellar density,
N – the total number of stars in the system,

R – the size of the system,
m – the typical mass of a star,
v – the typical speed of a star.

Relaxation Time: Back-of-the-envelope Calculation

The v and m dependences of the relaxation time can be found from a order-of-magnitude calculation.

Consider N stars of mass m each in a box of side R, and let these stars be fixed.

The number density of stars per unit volume is n, with $n \sim N/R^3$.

Then send another star through this box with speed v.

The moving star needs to pass within $r_0 \simeq Gm/v^2$ of one of the fixed stars, so that kinetic and two-body potential energies are equal.

In a time T, the expected number of stars passing within distance r_0 is $n\pi r_0^2 vT$.

Equating this expected number to unity gives the timescale, of order

$$T \sim \frac{(Rv)^3}{N(Gm)^2} \sim \frac{v^3}{n(Gm)^2}. \quad (1.13)$$

The $\ln N$ (i.e. $\ln \Lambda$) term comes from the fact that relaxation is a cumulative effect from two-body encounters with all stars.

More distant encounters each have less effect, but there are more of them. So these more distant encounters shorten the relaxation time by a factor depending weakly on N.

Relaxation Time (continued)

It is easier to remember T_{relax} in crossing times.

Assuming $N = (4/3)\pi R^3 n$, we find

$$\frac{T_{relax}}{T_{cross}} \sim \frac{N}{6\ln(N/2)}. \quad (1.14)$$

Consequences: Galaxies

Galaxies are $< 10^3 T_{cross}$ old and have $\gg 10^6$ stars.

Stellar encounters have negligible dynamical effect in galaxies.

Consequences: Globular Clusters

Globular clusters, may have $\sim 10^6$ stars and be $\sim 10^4 T_{cross}$ old.

Stellar encounters start to become important in GCs.

In the cores of globular clusters two-body relaxation is very important.

Conclusions

Stars are so compact on the scale of a galaxy that a stellar system behaves like a collisionless fluid (except in small and special regions such as the cores of galaxies and globular clusters).

In contrast, gas and dust are collisional.

This leads to two very important differences between stellar and gas dynamics in a galaxy.

- Gas tends to settle into disks, but stars do not.
- Gravity must be balanced by motion in stellar and gas dynamics, but, in equilibrium, gas must follow closed orbits (and in the same sense), but stars in general do not have to.
- Two streams of stars can go through each other and hardly notice, but two streams of gas will interact – formation of dense shocked regions (and will probably form stars).
- You can have a disk of stars with no net rotation, but not a disk of gas.
- Terms used: **rotation-support** and **pressure-support** to balance self-gravity.

  Pressure support refers to the velocity dispersion of stars (compensating for low net-rotation).
- Observationally, gas velocity dispersions are never more than $\sim 10\,\mathrm{km\ s^{-1}}$ while stellar dispersions can easily be $\sim 300\,\mathrm{km\ s^{-1}}$.

Types of galaxies

There are four broad categories of galaxies:

1. Spiral galaxies (Sa, Sb etc)
2. Lenticular (S0) galaxies
3. Elliptical galaxies (E0, E1 etc)
4. Irregular galaxies

Extra classes in some classification schemes:
cD galaxies – very massive ellipticals at the heart of large clusters.

dE galaxies – dwarf elliptical galaxies – small elliptical shaped galaxies, with old stellar populations.

dSph galaxies – dwarf spheroidals – even smaller than dE galaxies.

Sm and SBm galaxies – Magellanic spirals – prototype is the Large Magellanic Cloud (LMC).
Some galaxies do not fit easily into this scheme and are difficult to classify.
Spectra of galaxies determined by their stellar populations.

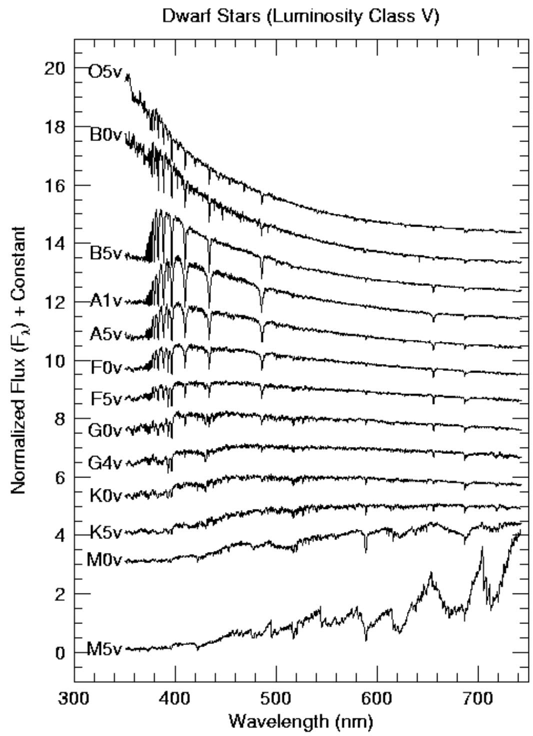

Figure 1.2: The spectra of different classes of stars. From hot OB stars through to cooler K and M stars. A combination of these stellar spectra make up the galaxy spectra. Elliptical galaxies tend to be dominated by older low-mass stars, while Spirals and Irregulars have more young high mass stars.

Disk/Spiral galaxies

These have masses of $10^6 M_\odot$ to $10^{12} M_\odot$.

The disk surface brightnesses tend to be roughly exponential, i.e.,

$$I(R) = I_0 \exp[-R/R_0] \tag{1.15}$$

with $I_0 \sim 10^2 L_\odot$ pc^{-2}.

The scale radius $R_0 \simeq 4$ kpc for the Milky Way.

The visible component is $\simeq 95\%$ stars (dominated by F and G stars for giant spirals), and the rest dust and gas.

The more gas-rich disks have spiral arms, and arms are regions of high gas density that tend to form stars; clumps of forming stars are observed as HII regions.

Disk galaxies have bulges which appear to be much the same as small ellipticals.

Substantial fraction (50%) of spirals are "barred", i.e. possess a central linear feature.

All disk galaxies seem to be embedded in much larger dark halos; the ratio of total mass to visible stellar mass is ~ 5, but we don't really have a good mass estimate for any disk galaxy.

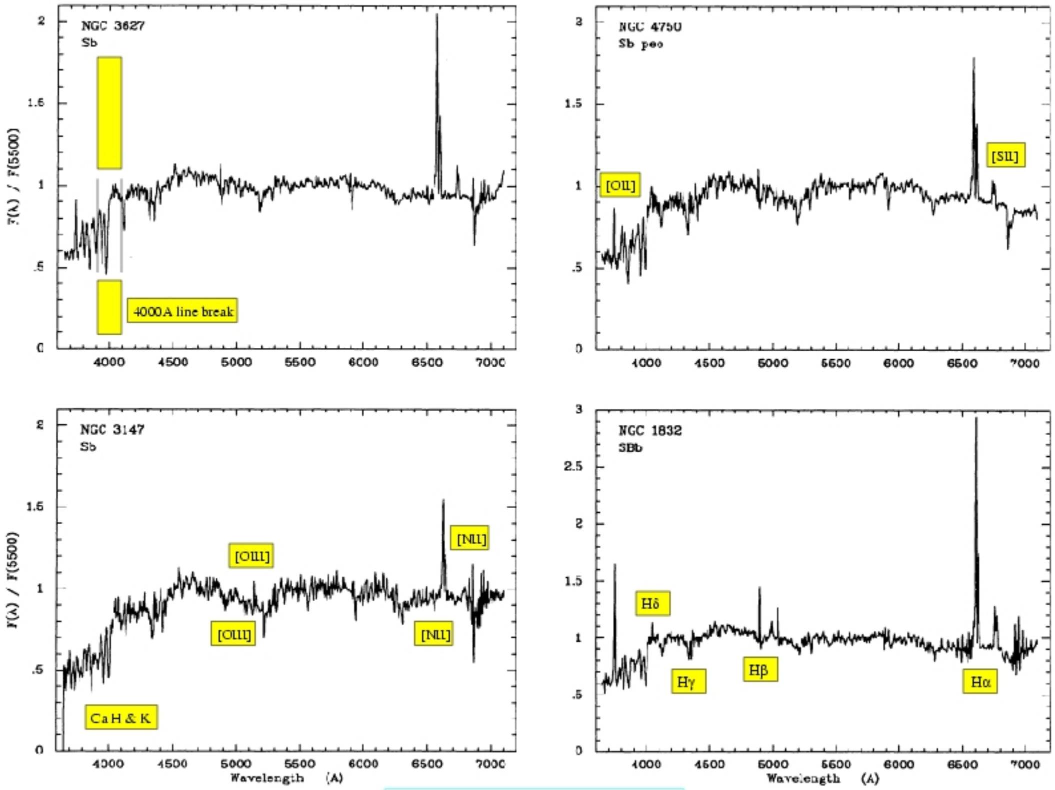

Figure 1.3: Spectra of a sample of spiral galaxies, showing the presence of emission lines, indicative of recent star-formation.

Elliptical galaxies

These have masses from $10^6 M_\odot$ to $10^{12+} M_\odot$.

There are various functional forms around for fitting the surface brightness, of which the best known is the de Vaucouleurs model

$$I(R) = I_0 \exp\left[-\alpha (R/R_0)^{\frac{1}{4}}\right] \tag{1.16}$$

with $I_0 \sim 10^5 L_\odot \text{ pc}^{-2}$ for giant ellipticals.

The functional forms are only fitted to observations over the restricted range in which $I(R)$ is measurable.

Do not be surprised to see different functional forms being fit to the same data.

The visible component is almost entirely stars (dominated by K giants for giant ellipticals), but there appears to be dark matter in a proportion similar to disk galaxies.

Ellipticals of masses $< 10^{11} M_\odot$ rotate as fast as expected from their flattening; giant ellipticals rotate much slower, and tend to be triaxial.

At the small end of ellipticals, we might put the globular clusters, even though they occur in conjunction with galaxies rather than in isolation. These are clusters of masses from $10^4 M_\odot$ to $10^{6.5} M_\odot$, consisting almost exclusively of old stars (some "blue stragglers").

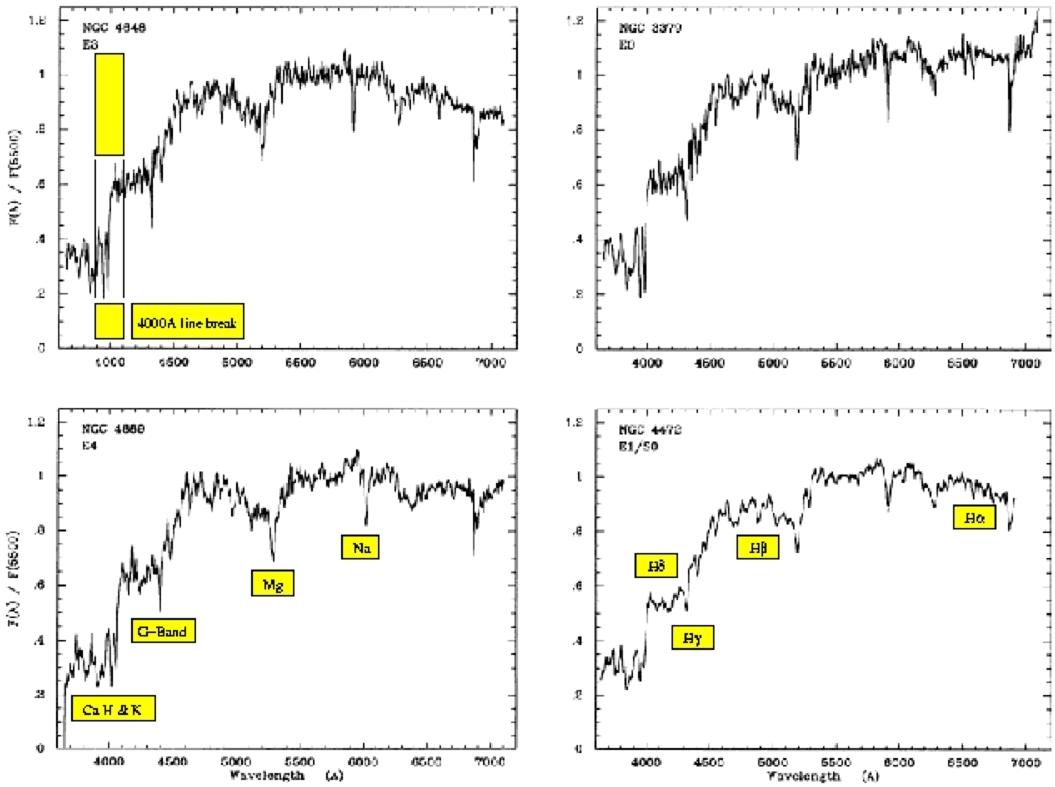

Figure 1.4: The optical spectra of a sample of elliptical galaxies, showing no emission lines and strong absorption features. This indicates an old stellar population.

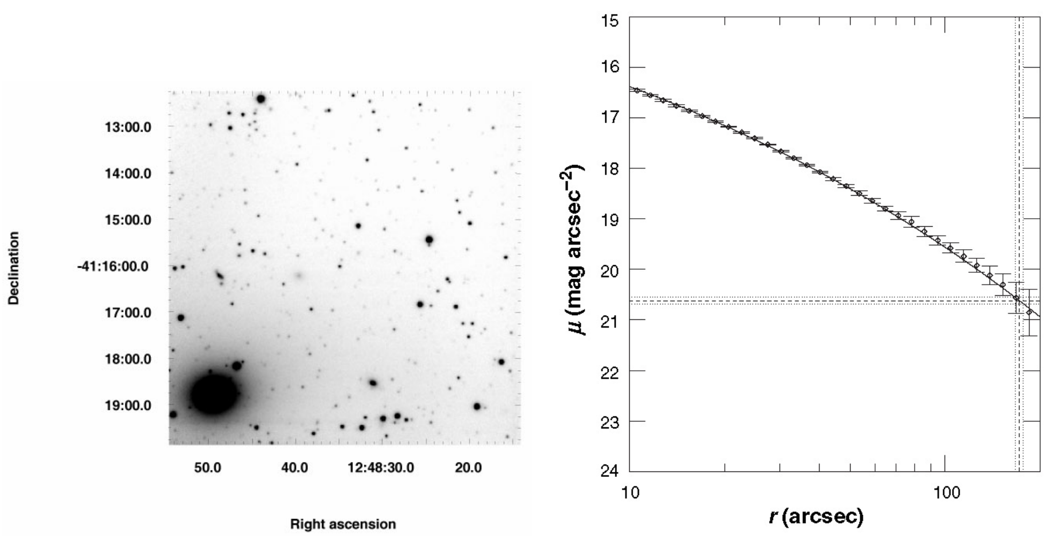

Figure 1.5: Left panel: The elliptical galaxy NGC 4696 as seen in the optical, showing the extended stellar halo. Right panel: the surface brightness of NGC 4696, as fit using a de Vaucouleurs profile.

Irregulars

Everything else! A mixture of objects that do not fit anywhere else.

They often have strong emission lines, and their starlight is dominated by young stars (B, A and F types). Nearby examples include the Large and Small Magellanic clouds.

Often appear to have a disturbed morphology (mergers/interactions) and are forming stars. Tend to be smaller galaxies.

Hubble types

On the whole, galaxy classification probably should not be taken as seriously as stellar classification, because there is not (yet) a clear physical interpretations of what the gradations mean.

Some physical properties do clearly correlate with the "Hubble types".

- Ellipticals: labelled as En, with $n = 10(1 - \langle \text{axis ratio} \rangle)$ (c.f projection effects)
- Lenticulars – disk galaxies without spiral arms: S0 and SB0. Lenticulars are rare in low-density environments (10%), but common in high density clusters (50%).
- Spiral galaxies with increasingly spaced arms, Sa etc. if unbarred, SBa etc. if barred.

Ellipticals are called "early-type" galaxies, and spirals "late-types".

Once thought to be an evolutionary sequence, this is now obsolete.

Our current understanding is that, if anything, galaxies tend to evolve towards early types.

But the old names (early type ellipticals/late type spirals) are still used.

We never see ellipticals flatter than about E7.

A "flatter" stellar system is unstable to buckling, and will eventually settle into something rounder (from simulations).

Note that bulges get smaller as spiral arms get more widely spaced. Theory for spiral density waves predicts that the spacing between arms is proportional to the disk's mass density.