Astronomy 1Y
Introduction to Cosmology

1 Section I: galaxies and their properties

The Sun inhabits a vast system of stars which we call the **Milky Way Galaxy**. From the Earth, the Milky Way appears to the unaided eye as a thin band of diffuse light stretching across the sky. Telescopes resolve this band of light into individual stars. The Milky Way appears as a thin strip because most of the stars in the Galaxy are found in a thin, flat disc with a central bulge. From our position embedded *within* the disc we see it edge-on.

The visible Milky Way is just our own galaxy seen 'edge-on'.

1.1 The Milky Way: facts and figures

visible MilkyWay
projected MilkyWay
COBE MilkyWay
2 micron MilkyWay
Sombrero Galaxy

mass *	$1.4 \times 10^{11}\ M_\odot$
radius of Sun's orbit	8.7 kpc
disc diameter	30 kpc
number of stars	4×10^{11}
bulge diameter	10 kpc
luminosity	$2 \times 10^{10}\ L_\odot$
halo diameter	100 kpc (approx)
absolute magnitude	-20.5 (M_V)
disc thickness **	1 kpc
rotation period **	2.5×10^{8} y

* inside Sun's distance from centre of the Galaxy.
** at Sun's distance from centre of the Galaxy.

1.2 Distance indicators

We can determine the distances to stars in the Galaxy using **distance indicators**, such as certain types of **variable stars**, or the **annual parallax** of stars (their change in apparent position over the year as seen from Earth). If we know the luminosity of a star, and measure its flux at Earth, we can estimate its distance because the flux drops off as the inverse-square of the distance. If we express this idea in terms of magnitudes we get the **distance modulus** formula. This relates the apparent magnitude (m) and absolute magnitude (M) of a star or galaxy to its distance modulus (μ) which is a simple function of its distance in parsecs (r) (see A1Y Stellar Astrophysics course):

$$m - M \equiv \mu = 5 \log r - 5. \qquad (1)$$

We can rewrite this equation as

$$r = 10^{0.2(m-M+5)}, \qquad (2)$$

so that if we know m and M we can calculate the distance, r. Certain variable stars provide us with an *estimate* of M (something we cannot measure directly, without travelling to the star!), so these distance indicators are basically **luminosity indicators**.

The two most commonly used variable star distance indicators are

We can measure distances in the Galaxy from stellar parallax (and geometry) or by measuring the apparent magnitudes of 'standard candles', such as RR Lyraes and Cepheids.

RR Lyrae stars These are A and F type giants*, which are pulsating. Their mean M_V is approximately constant, so they are a good example of a **standard candle** which is simply a class of object (star, galaxy etc.) assumed to have a predictable intrinsic luminosity. RR Lyrae stars are often found in globular clusters.

Cepheid variable stars These are F and G type supergiants, with $-6 < M_V < -2$, which pulsate with a period of ~ 1 day to ~ 50 days. Because of the existence of the **period luminosity relation** (see later) their absolute magnitude can be accurately estimated from their period. There are two types of Cepheids: type I and type II. Type II Cepheids are also known as W Virginis stars and are about 2 magnitudes fainter than a type I Cepheid of the same period.

Cepheid P-L plot

1.3 Where are we in the Milky Way?

There were several early attempts to map out the overall structure of the Milky Way. In the early 1900s Kapteyn studied how the

*The letters here denote the *spectral type* of a star, which is in turn related to its temperature and age. The sequence of spectral types, which runs O B A F G K M, is discussed in detail in the A1 stellar astrophysics course. For now all we need to remember is that the sequence gets cooler and redder from O to M. O type stars are very hot, blue stars which shine for only a few tens of millions of years; G type stars are much cooler, yellowish stars like the Sun, and shine for about 10 billion years.

number of stars of a given apparent magnitude – which could be related to the actual *space density* of stars – varied with direction. He found that the density seemed to fall off in all directions, suggesting that the Sun was located in the centre of the Galaxy. Kapetyn, however, took no account of **extinction** – the absorption of starlight by interstellar dust grains which makes stars appear dimmer. The apparent density drop-off was not a real effect but was due to extinction. Also, extinction restricted Kapetyn's survey volume to a very small part of the disc – too small to reveal its true shape. Shapley (1917) analysed the distribution of galactic **globular clusters** (GCs), measuring their distances using RR Lyraes. He found that GCs appeared to be roughly spherically distributed, centred on a point about 10 kpc from the Sun, which he argued was the centre of the galaxy. Oort and Linblad, in the 1920s, studied the *motions* of stars in the solar neighbourhood – revealing that the Sun was in a circular orbit around a point approximately coincident with the centre of Shapely's GC distribution.

The concept of the Galaxy (and other galaxies) is relatively recent – only since the 1920s.

The structure of the Galaxy

1.4 Rotation of the Galaxy

Oort and Linblad showed the the Galaxy does not rotate as a rigid body, but *differentially* – i.e., the angular speed of stars around the galactic centre depends on their distances from it. The inner part of the disc rotates like a rigid body: the speeds of stars are proportional to their distances from the galactic centre. The outer part of the disc is known as the **Keplerian** part, since the orbits approximately obey Kepler's laws. The transition from rigid-body to Keplerian motion occurs at a distance just inside the Sun's distance from the galactic centre.

The stars in our Galaxy orbit around the galactic centre, either with an approximately constant period (inner stars) or with an approximately constant speed (outer stars).

A **rotation curve** is a plot of rotation speed as a function of distance from the centre of the galactic disc. Fig. 1 shows a schematic rotation curve for the Galaxy.

The total mass of the Galaxy *interior* to the Sun's distance from the galactic centre can be estimated using **Kepler's third law** †,

$$G M_{\rm Gal} P^2 = 4\pi^2 a^3, \tag{3}$$

where $M_{\rm Gal}$ is the mass of the Galaxy interior to a (the Sun's distance from the centre), and P is the Sun's orbital period – about 2.5×10^8 yr. The mass outside the distance of the Sun has no effect on the Sun's orbit. Taking $a \simeq 8.5$ kpc we get $M_{\rm Gal} \simeq 10^{11}\ M_\odot$.

†This is only an approximation because the mass interior to the Sun's distance includes the central bulge and the disc. Since the distribution of the latter isn't spherically symmetric about the galactic centre this complicates things somewhat compared with the simple prediction of Kepler III, but we ignore this complication here.

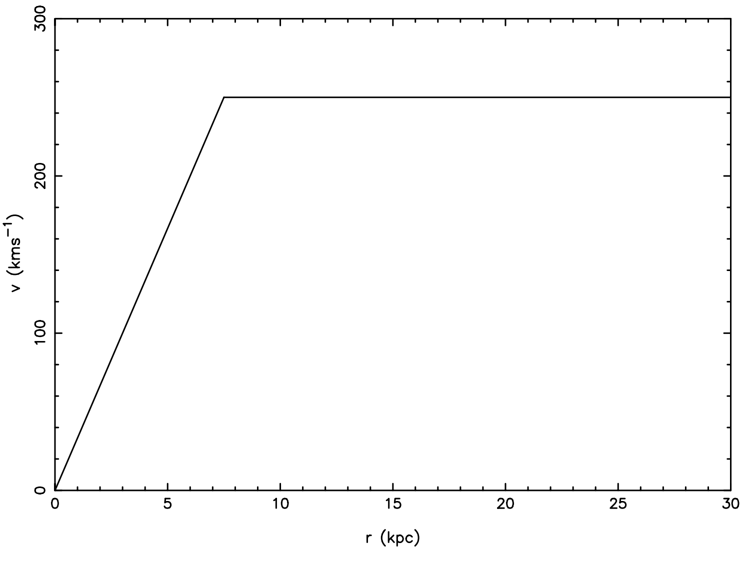

Figure 1: A schematic galaxy rotation curve.

1.5 The spiral structure of the Galaxy

The stars in the disc of the Milky Way Galaxy are not uniformly distributed but are found to lie along spiral arms, which wind tightly around the galactic bulge. The spiral arms are populated by large number of young O and B type stars and lanes of dust and molecular clouds – i.e., they are the sites of recent and ongoing **star formation**. The spiral structure of the galaxy can be mapped by measuring the emission of neutral hydrogen ('HI') throughout the disc. This radiation is emitted at a radio wavelength of $\lambda \simeq 21$ cm and is largely unaffected by extinction. Since the interstellar medium comprises primarily hydrogen, and is concentrated along the spiral arms, measurement of HI emission traces the spiral structure very well.

star formation in M51

Galactic 21cm emission

Because of the relative motion of the galactic hydrogen with respect to the Sun, the HI emission will be **Doppler shifted** to wavelengths other than 21 cm; the amount of the shift tells us how fast the HI clouds are moving. One can measure the amount of HI emission as a function of wavelength in different directions on the sky, and interpret the 'spread' in wavelengths around 21 cm in terms of the spatial distribution and differential rotation of the spiral arms along each line-of-sight. 21 cm maps of the Milky Way show the spiral structure to be somewhat fragmented and disjointed (see Fig. 2).

Observations of 21 cm radio emission from hydrogen atoms in the interstellar medium help us to map the shape of the Galaxy.

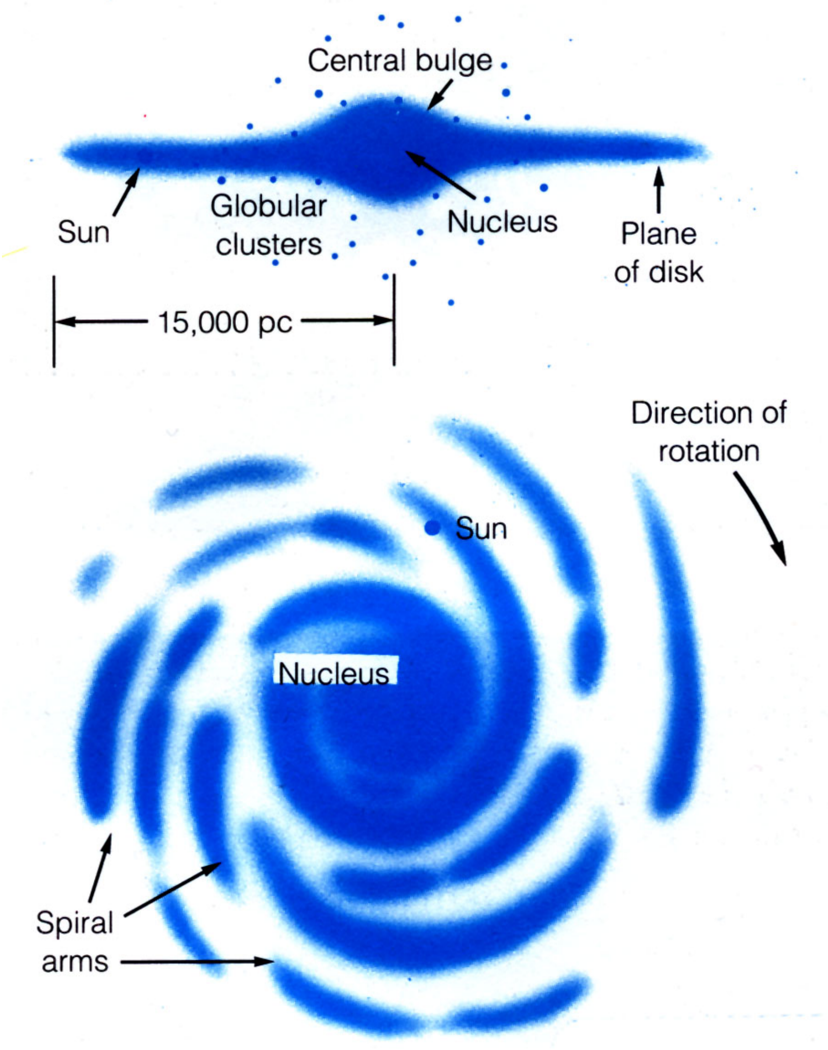

Figure 2: The structure of the Milky Way Galaxy.

1.6 The galactic halo

By plotting the rotation curve (from radio observations) out to several tens of kiloparsecs (kpc), astronomers have deduced that the galactic disc appears to be embedded in a roughly spherical **halo** of **dark matter**. The evidence for this halo comes from the fact that the rotation curve does not fall off as rapidly as one would expect if only the luminous stars in the disc were contributing to the gravity of the Milky Way (see Fig. 3.)

If we assume the mass in the Galaxy to be spherically symmetric rather than in a plane, and equate the gravitational attraction it exerts to the centripetal force necessary for circular motion around it, we get

$$\frac{mv^2}{r} = \frac{GM(r)m}{r^2}, \tag{4}$$

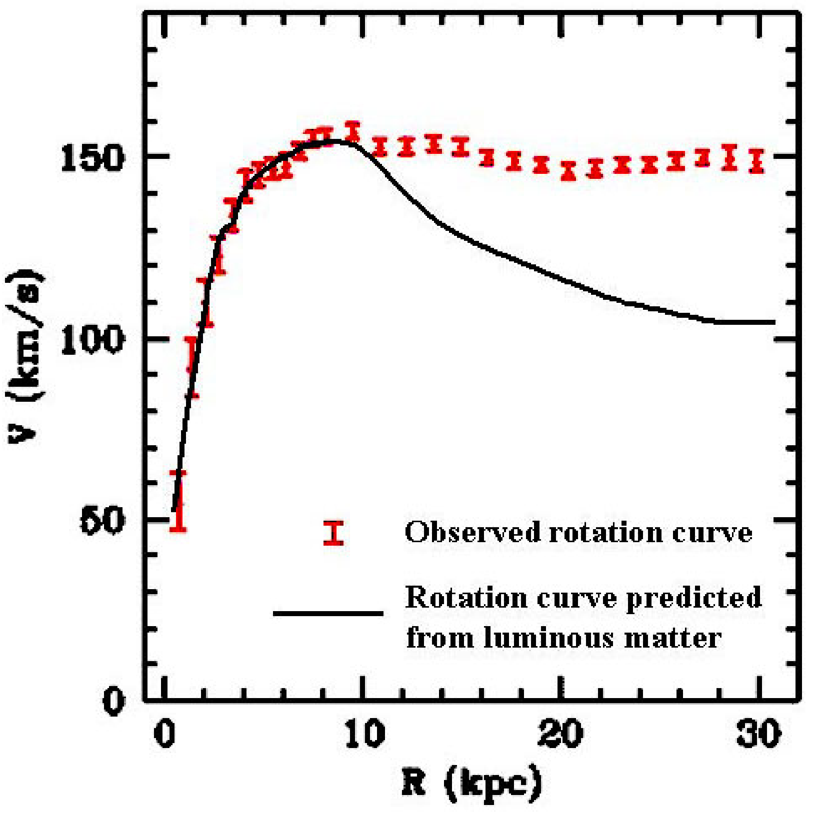

Figure 3: Typical rotation curve for a spiral galaxy like the Milky Way.

where m is the mass of an orbiting star, r is its distance from the galactic centre and $M(r)$ is the mass of the Galaxy within r. For stars outside the bulk of the Galaxy we have

$$v^2 = \frac{GM_{\rm Gal}}{r}, \tag{5}$$

$$\text{so that} \quad v(r) \propto r^{-\frac{1}{2}}. \tag{6}$$

We would therefore expect their speeds to fall off inversely with the square root of the distance. The shape of the galactic disc complicates the form of the rotation curve, but even taking this into account, the speeds are still predicted to fall off at large distances. In fact, the observed rotation curve is almost *flat* to distances well beyond the extent of the luminous disc. The presence of a nearly spherical **dark matter halo** extending well beyond the disc would explain this observation. (We return to the question of dark matter, and its implications for cosmology, in more detail later in the course).

The orbits of the outer stars are not consistent with the gravitational attraction of just the visible Galaxy. They imply that the Galaxy contains a lot of dark (i.e., not visible) matter in a spherical halo.

1.7 Formation and maintenance of the spiral arms

A **density wave** theory for the formation and maintenance of the spiral arms was proposed in 1960. This theory supposes the existence of a spiral-shaped wave pattern of high and low density regions, centred on the galactic bulge. These density waves cause gas and dust to 'pile up' in regions of higher density, causing stars in turn to pile up and become more concentrated in the spiral arms. The density wave theory *predicts* that the inside edge of the spiral arms are the most active star-forming regions.

The spirals in some galaxies represent regions of low and high density. The spiral arms are 'bottlenecks' of stellar congestion, which individual stars move into and through.

In the absence of the density wave the spiral structure of a disc galaxy would be much more chaotic and disordered. (In fact, given the fragmented appearance of the spiral arms in Fig. 2., it is thought that the role of the density waves in forming and maintaining the spiral arms was less pronounced for the Milky Way than for other spirals).

1.8 The nature of the "nebulae"

The Messier catalogue

Edwin Hubble

M31 (Andromeda)

The Messier catalogue contains many galaxies. Previously these were thought to be **nebulae** – i.e., gas clouds *within* the Milky Way. Examples include the Andromeda Spiral, M31. In 1924 Edwin Hubble measured the distance to M31 using Cepheid variables. He found that M31 was much too distant to be inside the Milky Way and, by deducing its intrinsic diameter from its apparent angular diameter, he found that M31 was in fact comparable in size to the Milky Way. Hubble then embarked on a systematic survey and classification of nearby galaxies. He identified three main types of normal galaxies: **spirals**, **ellipticals** and **irregulars**.

Elliptical	E0-E7	spheroidal; the number is defined as $n = 10(1 - b/a)$
Dwarf elliptical	dE	spheroidal; very low mass, luminosity
Lenticular	S0	disc-like; no spiral structure
Spiral	Sa-Sc	disc-like; spiral arms
Barred Spiral	SBa-SBc	disc-like; elongated, bar-like nucleus
Irregular I	Ir I	disc-like; spiral structure, but poorly organised
Irregular II	Ir II	'misfits'

An Sa galaxy has a large central bulge and small, tightly wound spiral arms. An Sc galaxy has a small central bulge and wide, open spiral arms.

1.9 Properties of normal galaxies

Spiral galaxies have diameters in the range 10 to 100 kpc. The mass of the disc is 10^{11} - $10^{12} M_{\odot}$. the spiral arms contain OB stars, dust and molecular clouds. The disc rotates around the centre of the galaxy.

e.g., M31, M51, M100

NGC4414
NGC2997

Elliptical galaxies have diameters in the range 1 to 100 kpc, and masses in the range 10^{7} - $10^{13} M_{\odot}$. They are spheroidal in shape, with a smooth brightness profile. They have little interstellar gas. There is a large population of dwarf ellipticals.

e.g., M32, M87

M87

Irregulars are irregular in shape – possibly due to recent collisions or mergers with other galaxies.

e.g., the Large Magellanic Cloud.

LMC

Ellipticals are old systems: since they have little interstellar gas and dust, they have very little current star formation. In spirals, on the other hand, star formation is still going on – particularly in the spiral arms. (This is why the spiral arms contain O and B stars).

The visible **Mass-to-light ratio** is higher for ellipticals than spirals. This is consistent with there being very little current star formation in ellipticals: they contain a smaller proportion of young, massive stars than do spirals.

Stars are still being formed in spiral galaxies, making them relatively rather luminous.

1.10 The Hubble tuning fork diagram

Tuning fork diagram

Hubble's classification is often represented via a **tuning fork diagram** (see Fig. 4). For many years the prevailing belief was that ellipticals evolve into spirals, from left to right in the tuning fork (although it should be pointed out that Hubble did not argue for the tuning fork diagram as an evolutionary sequence). More recently, the discovery that spirals contain many newly-formed stars led to speculation that, conversely, spirals evolve into ellipticals. However, spirals contain many old stars too, and it is now generally accepted that the spirals and ellipticals which we observe today evolved separately, as part of a much more complex overall pattern of galaxy formation.

The Hubble tuning fork diagram is not and evolutionary sequence.

1.11 Active galaxies

Galaxies whose luminosity is greater than that solely due to the stars which they contain are known as **active galaxies**. Their cores are known as **active galactic nuclei** (AGN). All active galaxies are observed at high "redshifts" (see later) indicating they are very distant. Light travels at a finite speed, so we therefore see them

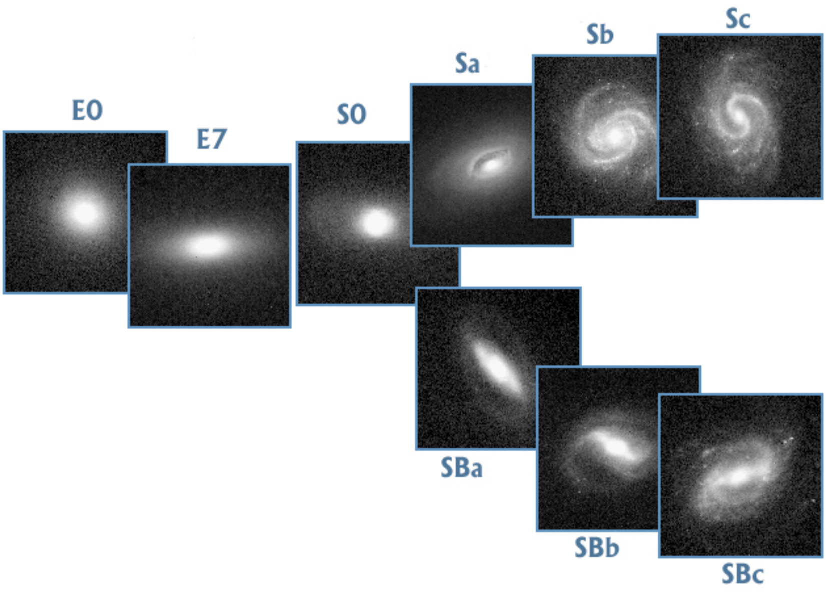

Figure 4: Hubble's tuning fork galaxy classification.

as they were in the distant past. This indicates that they represent a phase in the early history of galaxy formation, now over. We will consider three types of active galaxy: radio galaxies, Seyfert galaxies and quasars.

1.11.1 Properties of radio galaxies

Cygnus A

- Galaxy type = elliptical or giant elliptical (cD) galaxy
- Ratio of radio to optical luminosity in the range 0.1 – 10.
- Radio source shape is double-lobed (e.g., Cygnus A) or compact central source, often with a *jet* (e.g., M87).
- Compact sources often vary on timescales of days, implying that the size of the emitting region is no more than a few light-days across.
- The radio source spectrum is usually **synchrotron** radiation, indicating the presence of a strong energy source and intense magnetic field capable of accelerating particles (e.g., electrons) close to the velocity of light. Radio lobes are the result of relativistic beaming (see also the discussion of *pulsars* in A1 stellar astrophysics).

1.11.2 Properties of Seyfert galaxies

NGC7742

- Seyfert galaxies are spiral galaxies with unusually luminous, blue nuclei.
- About 10% of Seyfert galaxies show strong radio emission; some also have jets.
- Optical spectra show strong **emission lines**, formed in a highly ionised gas. Both narrow and broad emission lines are observed (broadening is assumed due to Doppler motions of the gas); broad lines are thought to be formed close to the core of the nucleus, in gas moving at several thousand $\mathrm{km\,s^{-1}}$.
- Short exposure images of Seyfert galaxies reveal only the nucleus – galaxies appear star-like.
- Few nearby spirals show the features of Seyfert galaxies, suggesting that they are an evolutionary phase in the early life of a galaxy.

1.11.3 Properties of quasars

3C273

- Quasars were first discovered in 1960. They were identified as star-like in appearance but with radio emission and optical spectra which matched no known stars (hence the name, short for "quasi-stellar object"). Their spectra contained strong emission lines, eventually identified as Balmer lines from atomic hydrogen, but redshifted to much longer wavelengths than in the laboratory.
- The conventional interpretation of this redshift is that it is due to the **Hubble expansion** (see later), implying that quasars are at very large distances, and are observed to have very large recession velocities.
- Quasar spectra contain **highly ionised** emission lines of H, He, and often C, N, O, indicating a very intense, hot radiation field. Lines are often very broad, indicating very rapid motions of the hot gas in the emitting region. Many spectra also show weak **absorption lines**.
- Quasar optical luminosities are up to 10 to 100 times that of a normal galaxy.
- Many quasars vary in luminosity over timescales of days or weeks, indicating a very compact emitting region of only 10 to 100 AU in diameter.

- About 10% of quasars are strong radio sources – emission due to synchrotron radiation. Some quasars have observed optical or radio jets.

1.12 Quasars: galaxies in infancy

The evidence for quasars being at cosmological distances now appears conclusive, particularly since the Hubble Space Telescope (HST) has recently observed quasar host galaxies at the same redshift. If quasars are so distant however, how can such a high luminosity be produced in such a small volume? The accepted answer to this puzzle is that a quasar is powered by a supermassive black hole at its core. Infalling material releases large amounts of energy as it is swallowed up by the black hole; there is no other satisfactory model which can provide a sufficiently luminous source of energy.

In the standard model, a quasar is thought to be the core of a very young galaxy. The black hole forms at its centre during the chaotic early collapse of the protogalactic gas cloud. Its mass may be as much as $10^8 M_\odot$. Infalling matter then forms an **accretion disc** around the black hole. The energy released by this infalling matter produces two accelerated jets of particles moving at relativistic velocities, which stream out from the accretion disc, producing beams of synchrotron radiation (see Fig 5).

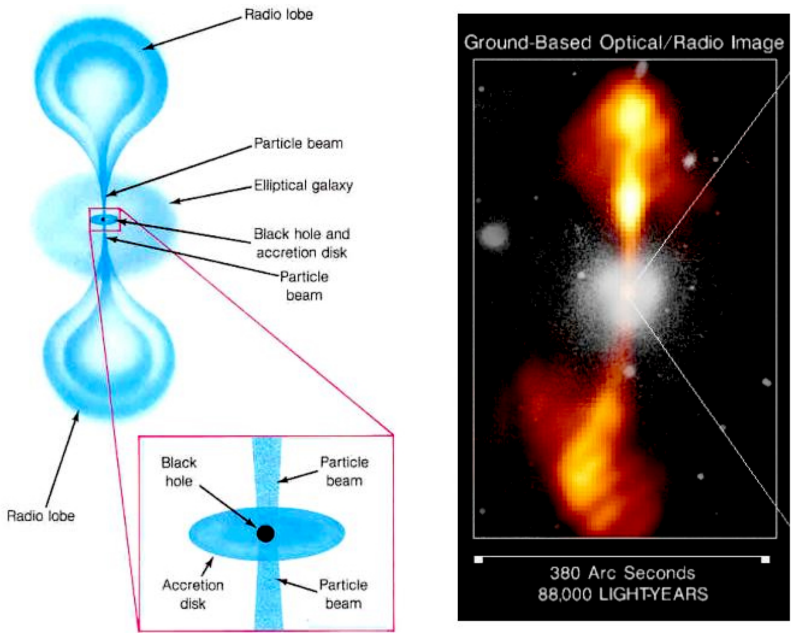

Figure 5: Quasar standard model.

Active galaxies are probably all galaxies in their early stages of formation, seen at different times and different orientations.

Seyfert galaxies and radio galaxies can be described by a similar model, but with diminished intensity – i.e. these are *less active descendants* of quasars.

1.13 Quasar absorption lines

quasar spectrum

Absorption lines are very common in quasar spectra – usually at a different redshift (almost always lower than that of the quasar). These lines are thought to be due to the absorption of light from the quasar by the extended halos of intervening galaxies. Quasar absorption spectra therefore provide useful information on the environment of newly-formed galaxies.

Some absorption spectra show only H absorption lines – i.e., the light from the quasar has passed through intervening clouds which have not yet had time to undergo stellar processing of heavier elements (again, see A1 stellar astrophysics for further discussion). These lines are due to absorption by **pre-galactic clouds**. Quasar absorption spectra can, therefore, constrain the abundance of **primordial elements** (see Section 4).