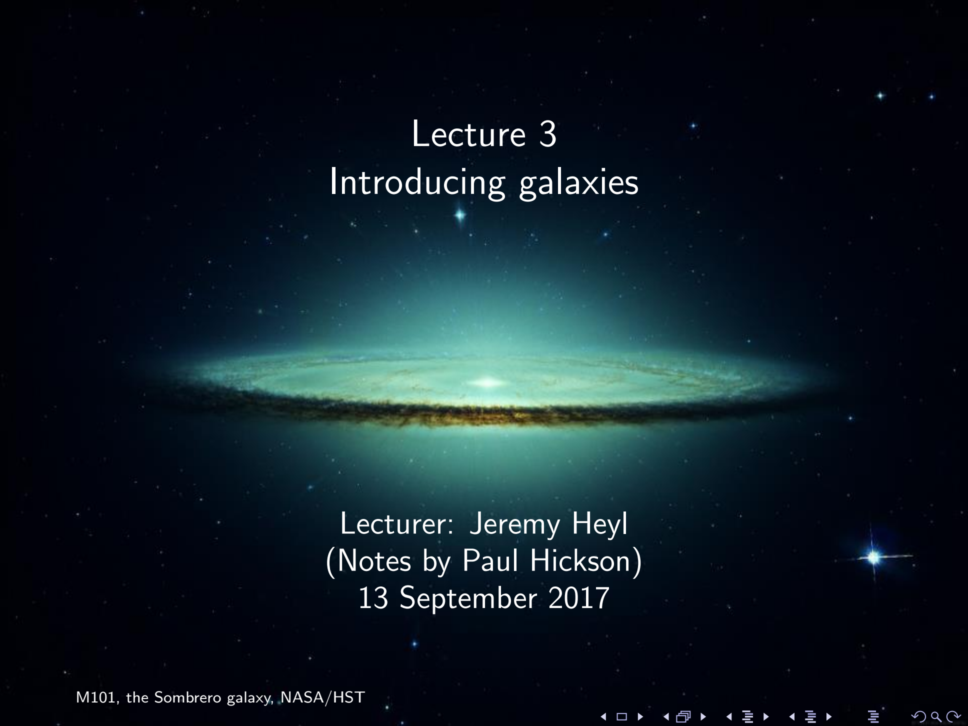


Lecture 3
Introducing galaxies

Lecturer: Jeremy Heyl
(Notes by Paul Hickson)
13 September 2017

M101, the Sombrero galaxy, NASA/HST

1.2 Our Milky Way

The Sun is one of several hundred billion stars in a galaxy called the **Milky Way**, or just the **Galaxy**.

Its centre is found in the southern sky, in the constellation of Sagitarius, and is shown in the photo below. The two small objects seen at the left are satellite galaxies, the large and small Magellanic Clouds.

B. Gilli, ESO

Our Milky Way

The main components of the Galaxy are:

- the **disk** - thin rotating disk of stars, gas and dust. The Sun is located about 8 kpc from its centre.
- the **bulge** - central concentration of stars
- the **nucleus** - compact central star cluster and massive black hole
- the **halo** - tenuous extended spherical distribution of old stars and globular clusters
- the **dark halo** - extended, roughly spherical, envelope of dark matter

The space between the stars is occupied by the **interstellar medium** (ISM), which consists of gas, dust, charged particles, photons, neutrinos, and dark matter.

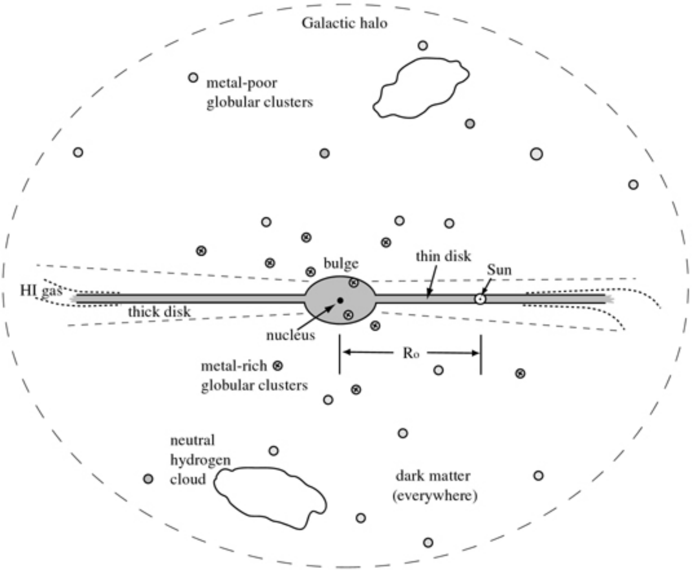


Fig 1.8 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Schematic side view of the galaxy

The disk

One distinguishes the **thin disk** and **thick disk**

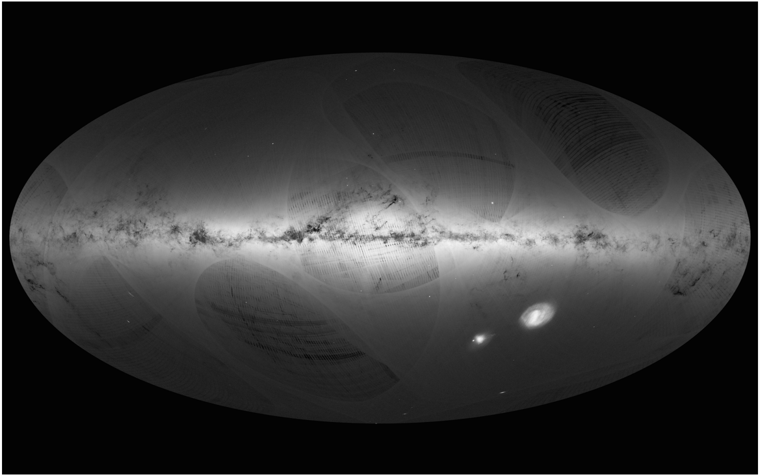
The thin disk has a scale height of $\sim 300 - 400$ pc. The thick disk about 1 kpc.

The thin disk contains 95% of the stars, all the young stars and nearly all the gas.

The thick disk contains old stars that have lower metallicity.

The gas is primarily neutral hydrogen and helium, confined to within ~ 100 pc of the plane (at the radius of the Sun, greater at larger radii).

Stars, gas and dust in the disk revolve about the centre in roughly circular orbits with a typical velocity of ~ 200 km/s. The Sun takes ~ 250 Myr to complete one orbit.



Gaia's first map (1.14 billion stars) ESA

The bulge, nucleus and halo

The bulge has about $1/3$ the mass and luminosity of the disk. The bulge rotates more slowly, about 100 km/s, and its stars have large random velocities.

The nucleus contains a black hole of about 4.5 million $M_\odot$.

The halo contains just a few percent of the Galaxy's stars. These stars have low metallicity and are presumed to be very old.

The velocities of stars are too large to be explained by the visible mass alone. From this we infer that most of the mass of the galaxy is in a non-luminous form called dark matter, which is less centrally concentrated than the stars.

Photoionization

Gas in the disk absorbs light from stars, primarily in the ultraviolet (UV) region of the spectrum. This results in excitation and ionization of the atoms.

Regions in which hydrogen is almost all ionized are called **HII regions** (neutral hydrogen is HI).

Notation: HII $=$ H$^+$, Ne V $=$ Ne^{+4}, etc.

The process by which an energetic photon ionizes an atom is called **photoionization**. For hydrogen, an energy $\Delta E \geqslant 13.6$ eV is required to remove an electron from the ground state. Since

$$\Delta E = h\nu = \frac{hc}{\lambda},$$

this corresponds to a wavelength of 912Å or less, which is in the UV.

Recombination

When ions recombine with electrons, they are normally in an excited state. As the electrons decay to lower energy levels, **recombination radiation** is produced.

Transitions of electrons from excited states to lower energy levels, and the ground state, produce radiation at specific wavelengths, according to the change in energy ΔE

$$\Delta E = h\nu = \frac{hc}{\lambda}.$$

For example, a transition from the $n = 2$ level to $n = 1$ (a change of 10.2 eV) in atomic hydrogen produces a Lyman-α emission line with a wavelength of 1216 Å.

The energy levels are proportional to the square of the electric charge of the nucleus. As a result, transitions to low energy levels in heavy atoms such as Fe can produce X-ray photons.

Collisions

Atoms can also be excited or ionized by collisions if the gas is very hot.

The typical kinetic energy of a particle in a gas at temperature T is $\sim kT$. If this is comparable to the energy difference between states, excitation will occur. If it is greater than the ionization potential, ionization will occur.

For example, if $T = 10^5$ K. Then $kT = 8.6$ eV.

Atoms can also be de-excited by collisions. If the density is high enough, this may happen before the atom has time to decay by emitting a photon.

For each atomic transition, there is a “critical” density at which the line is close to its maximum strength. This depends on the lifetime of the excited state.

Collision rate

How often do collisions occur?

The average rate at which a given atom, moving at speed v will collide with other atoms is given by the collision rate equation,

$$\text{collision rate} = n\sigma v$$

where n is the number density of atoms (number of atoms per unit volume), σ is the **cross-section** for the collision, and v is the relative velocity.

If we model Hydrogen atoms as hard spheres of radius equal to the **Bohr radius** a_0, the collision cross section will be $\pi(2a_0)^2 = 4\pi a_0^2$, where

$$a_0 = \frac{h^2}{4\pi^2 m_e e^2} = 0.529 \times 10^{-10}\ \text{m}.$$

(The text book omits the factor of 4 in the cross section).

Forbidden lines

Some excited states have a much longer lifetime than others. These occur when no downward electric-dipole transitions are allowed by quantum-mechanical selection rules. Such states can only decay by electric-quadrupole or magnetic dipole transitions, which are much less probable.

Transitions from these states do not occur unless the density is very low.

These lines are called **forbidden lines**. They do not occur on Earth because the density is too high in even the best laboratory vacuum. However they are often seen in interstellar space where the typical density is much lower.

Forbidden lines are denoted by square brackets, eg. [OIII] 5007Å.

Fine structure

Transitions can occur that involve the interaction of the electron's spin with its orbital angular momentum. This results in closely spaced energy levels (the energy difference is smaller by about a factor of α^2, where $\alpha = e^2/4\pi\varepsilon_0\hbar c \simeq 1/137$ is the fine structure constant).

Such transitions emit (and absorb) photons that are less energetic, typically having wavelengths in the far infrared region of the spectrum $(10 - 300$ um$)$.

These transitions are important at lower temperatures as less energy is needed to excite them.

Important lines are CII 158 um, and OI at 63 um and 145 um, which are excited at a temperature $T \sim 100$ K.

Hyperfine structure

Interactions between the spin of the electron and the spin of the nucleus produce an even finer splitting of spectral lines.

The most important example occurs in neutral hydrogen. The state in which the electron an proton spins are parallel is more energetic by 5.6×10^{-6} eV, which corresponds to a photon having a wavelength of 21 cm.

This 21-cm radiation can be detected by radio telescopes, and is an important tool for mapping the density and velocity distribution of neutral hydrogen in galaxies.

The lifetime of the upper state is about 11 Myrs, so these transitions don't happen very often, but there are so many H atoms in the galaxy ($\sim 10^{66}$) that this radiation is abundant.

Molecular transitions

Molecules have quantized rotational and vibrational states. Transitions between these states result in the emission (or absorption) of photons, typically in the infrared and sub-mm regions of the spectrum.

Vibrational transitions typically have wavelengths of a few um.

The most abundant molecules are H_2, CO, H_2O, HCN, CS, NH_3, However more than 200 molecular species have been identified in interstellar space, including complex organic molecules.

CO has strong transitions at 1.3 mm and 2.6 mm wavelength that require temperatures of only $10 - 20$ K for excitation.

The ratios of line strengths at different wavelengths (energies) provide information about the temperature and density of the gas.

Masers

Near sources of intense radiation, such as hot stars or active galactic nuclei, it is possible to have more molecules in excited states than would be found in thermal equilibrium.

Stimulated emission may then occur which generates coherent radiation (as in a laser).

We then see small intense spots of microwave radiation at the wavelength or frequency corresponding to the transition.

Common transitions for molecular masers are 1.7 GHz for OH and 22 GHz for H_2O.

Doppler shift

The **radial velocity** V_r of a source is the component of velocity along the line of sight to the source (negative if the source is approaching us).

We can infer the radial velocity of the source of the emission by the Doppler shift of spectral lines.

For speeds that are small compared to the speed of light ($V_r \ll c$), we can use the nonrelativistic formula

$$1 + z \equiv \frac{\lambda_{\text{obs}}}{\lambda_{\text{em}}} \simeq 1 + \frac{V_r}{c}.$$

where z is the **redshift**, λ_{obs} is the observed wavelength and λ_{em} is the emitted wavelength (i.e. the wavelength that would be measured for the gas in a laboratory on Earth).

Bremsstrahlung

Hot ionized gas emits continuum radiation through a process known as **bremsstrahlung** or **free-free** radiation.

This occurs when free electrons encounter ions and are deflected by the electrostatic field. The change of direction is a form of acceleration, and produces radiation.

Quantum mechanically, one can regard this as a transition between unbound states of the electron (a free-free transition). Since the states are not bound, they are not quantized, so the radiation is not confined to specific wavelengths.

We see bremsstrahlung emitted at radio frequencies by hot gas ($T \sim 10^4$ K) in HII regions.

We also see it in the form of X-rays emitted by very hot gas ($T \sim 10^6$ K) in galaxies and also from the intergalactic medium in groups and clusters.

Synchrotron radiation

Continuum radiation is also produced by electrons moving through magnetic fields. They feel an electric force that continuously deflects them, resulting in radiation.

If the electrons are moving a relativistic speeds, which is usually the case, the radiation is called **synchrotron radiation**.

Synchrotron radiation is seen in supernovae remnants, radio galaxies, active galactic nuclei, and astrophysical jets. It can range from radio to X-ray wavelengths depending on the electron energy.

Dust

About 1% of the mass of the ISM is in the form of dust.

This consists of small grains of silicate material and carbon typically smaller than ~ 1 um.

The grains condense in the atmospheres of cool stars and are ejected into the ISM by stellar winds.

Dust is an effective absorber of radiation at wavelengths comparable to and smaller than the size of the grains.

The dust grains are heated by diffuse stellar radiation, and emit **thermal radiation** according to their temperature.

Typically, $T \sim 10 - 20$ K which results in radiation that peaks around 200 um.

Extinction

When light propagates through a dust cloud, photons are absorbed and scattered (re-emitted in a different direction). As a result, the intensity of the light decreases.

The rate of change of intensity with distance s, at wavelength λ, is given by

$$\frac{dI_\lambda}{ds} = -\alpha(\lambda) I_\lambda$$

where $\alpha(\lambda)$ is the **absorption coefficient**.

This equation has the solution

$$I_\lambda(\tau) = I_\lambda(0) e^{-\tau}$$

where

$$\tau = \int \alpha(\lambda) ds$$

is the **optical depth**.

A related quantity is the **opacity**, $\kappa(\lambda)$ defined by $\alpha(\lambda) = \kappa(\lambda)\rho$, where ρ is the mass density.

Extinction

We see that the light from the source is attenuated exponentially as it propagates through the cloud. For a constant α, $\tau = \alpha s$ so the optical depth increases with the size of the dust cloud.

Integrating over the solid angle subtended by the source gives

$$F_\lambda(\tau) = F_\lambda(0)e^{-\tau}.$$

This corresponds to an *increase* in the apparent magnitude of a star, called **extinction** A, when dust is present,

$$A = -2.5\log(e^{-\tau}) \simeq 1.086\,\tau.$$

The opacity depends on wavelength. In the range 3000 Å $- 1$ um, $\kappa \propto 1/\lambda$ approximately.

The extinction, in the V band, at the galactic pole is $A_V \simeq 0.15$, which corresponds to approximately 13% light loss.

Celestial coordinates

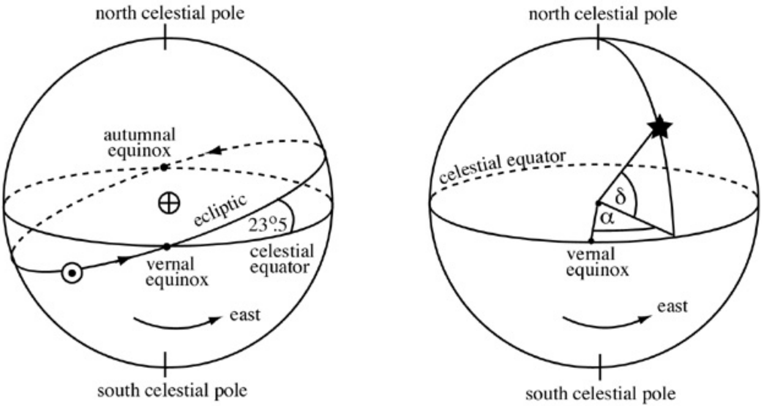


Fig 1.9 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Right ascension α and delclination δ are similar to longitude and latitude on the celestial sphere. These coordinates are fixed in space and do not rotate with the Earth.

Celestial coordinates

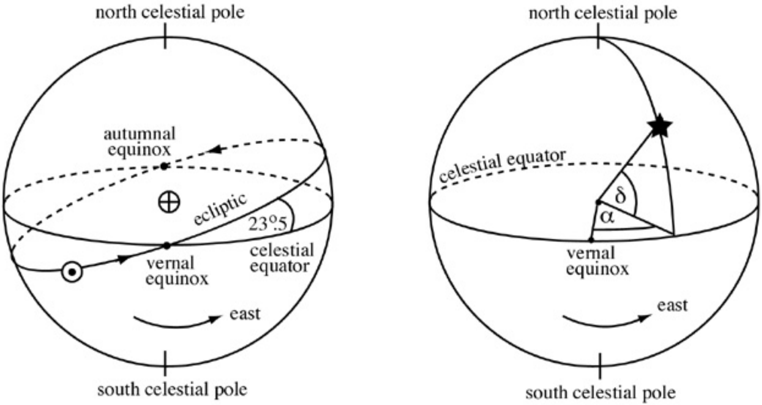


Fig 1.9 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The path traced by the Sun over the course of a year, the **ecliptic**, is inclined by 23.5 degrees due of the tilt of the Earth's axis.

Right ascension is measured from the **vernal equinox** - the point where the Sun crosses the celestial equator northward.

Celestial coordinates

The path traced by the Sun over the course of a year, the **ecliptic**, is inclined by 23.5 degrees due of the tilt of the Earth's axis.

Right ascension is measured from the **vernal equinox** - the point where the Sun crosses the celestial equator northward.

Because of precession of the Earth's axis, The coordinates of stars slowly change.

Because of this, the time between successive vernal equinoxes (the **tropical year** is about 20 minutes shorter than the Earth's orbital period (the **sidereal year**).

Because of precession, when giving the coordinates of a star one must also specify the time at which they are valid. Normally coordinates are "precessed" to a common epoch, such as J2000: 30 December 2000 at 11:58:55.816 UTC (Coordinated Universal Time).

Celestial coordinates

The great circle passing through the zenith and the celestial poles is called the **meridian**. It crosses the observer's horizon at points that are due north and south.

As the Earth rotates, stars rise in the east and set in the west. They are highest in the sky when due south (in the northern hemisphere), when they cross the meridian.

The right ascension of the meridian is called the **sidereal time** it depends on the time of day, the day of the year, and the observer's longitude.

Because of the Earth's motion around the Sun, the solar day (mean time between successive crossings of the meridian by the Sun) is longer, by about 4 minutes, than the sidereal day (time between successive crossings of the meridian by stars.

There are ~ 366.25 sidereal days (Earth rotations) in a year.

Galactic coordinates

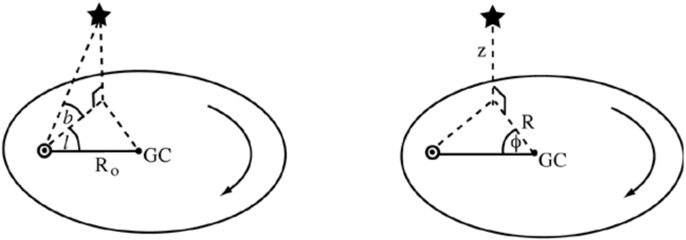


Fig 1.10 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Galactic longitude l and latitude b are measured in a Sun-centred spherical coordinate system, aligned with the plane of the Milky Way. The zero of longitude is the direction to the galactic centre.

The north Galactic pole (NGP) is located at
$\alpha = 12^{\mathrm{h}}49^{\mathrm{m}}, \delta = 27^\circ 24'$ and the Galactic centre (GC) is at
$\alpha = 17^{\mathrm{h}}45^{\mathrm{m}}40.0^{\mathrm{s}}, \delta = -29^\circ 00' 28.1''$ (J2000).

We will also use a cylindrical coordinate system (R, ϕ, z) centred on the galaxy.