INTRODUCTION AND BASIC CONCEPTS

1.1 Stars in the Broader Context of Modern Astrophysics

The study of stars continues to be at the very core of modern astrophysics more than 5000 years since its inception. Astronomy may well be the oldest science, and when early bronze age man looked up at the night sky he or she saw mostly stars. The signs of the zodiac—the first attempt at classifying, or at least grouping, stars—have their origin in Mesopotamia, the land between the Tigris and Euphrates rivers (modern Iraq) where the Sumerian, Assyrians and Babylonians civilisations flourished.

Today stars play a key role in many branches of astronomy, as well as being of interest in their own right.

- 'The epoch of reionisation', which has been described as the 'last frontier in observational cosmology' marks the period—approximately 600 million years after the Big Bang—when the Universe experienced its last 'phase-change': it changed from being mostly neutral to being mostly ionised (see Figure 1.1).

  This transition was caused by the 'First Stars' which are believed to have been very massive and highly luminous *at wavelengths below 912 Å*. Photons with such short ultraviolet wavelengths have energies $E = h\nu >$ 13.6 eV, higher than the ionisation potential of hydrogen. The First Stars were thus able to ionise large volumes around them; when sufficient numbers of such stars had formed, their ionised surroundings, or H II regions, overlapped and most of the volume of the Universe became transparent and accessible to observations from Earth.

  A great deal of effort, both theoretical and observational, is currently being devoted to elucidating the nature of the First Stars.

- When massive stars explode, either as supernovae or gamma-ray bursts, they can outshine a whole galaxy. They can thus be observed at the largest distances, rivalling galaxies and quasars (the centres of galaxies

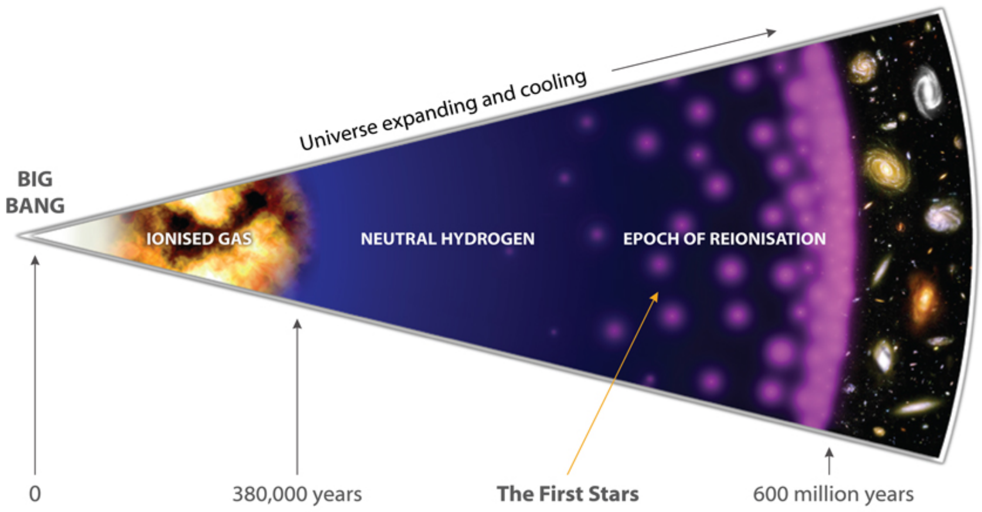

Figure 1.1: Schematic representation of the 'Epoch of Reionisation'. Time progresses from left to right.

hosting supermassive black holes) as probes of the distant, and therefore young, Universe. A gamma-ray burst is thought to mark the end of a *massive and rapidly rotating star*, when its core collapses directly into a black hole and two extremely energetic jets of plasma are emitted from its rotational poles at nearly the speed of light (see Figure 1.2). At present, the most distant gamma-ray burst (GRB) known is at at redshift $z \sim 9.4$; the massive star that produced it formed when the Universe was only ~ 500 Myr old, or $\sim 4\%$ of its present age. Observations of these very distant GRBs give us a unique window on the early stages in the evolution of the Universe.

- The properties of stars are sufficiently well known that it is possible to reconstruct, using a mixture of theory and observations, the emergent spectrum of a whole population of stars, i.e. a whole galaxy. This 'spectral synthesis' technique is now used widely to interpret photometric and spectroscopic observations of galaxies over most of the history of our Universe.

- In the last thirty years we have come to realise that many (most) stars have their own planetary systems. At the time of writing (Aug 2025), there are more than 4500 planetary systems, more than 6000 planets and $\sim$ 1000 multiple planet systems known (http://exoplanet.eu/catalog). Nearly all of these have been found by very precise observations of their *stars*, by either radial velocity, photometry (transiting planets), or mi-

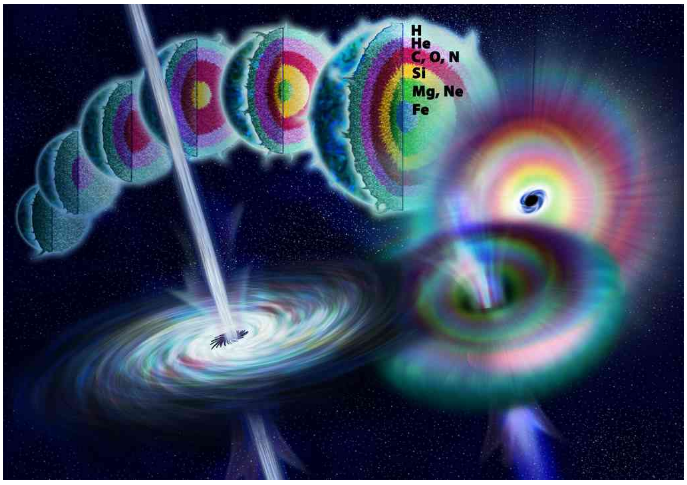

Figure 1.2: Artist's impression of the late stages in the evolution of a massive star, leading to a gamma-ray burst.

crolensing measurements.

- Many (most) stars are in binary or multiple systems. Massive stars (with masses of more than $\sim$ 10 times the mass of the Sun) reach extreme physical conditions at the end of their lives, becoming either neutron stars or black holes. Binary systems consisting of neutron stars or black holes will eventually merge and, in the process, emit gravitational waves. Gravitational waves are 'ripples' in space-time, predicted by Einstein's theory of general relativity. They were first detected 100 years later, with the *Laser Interferometer Gravitational-Wave Observatory* (LIGO),

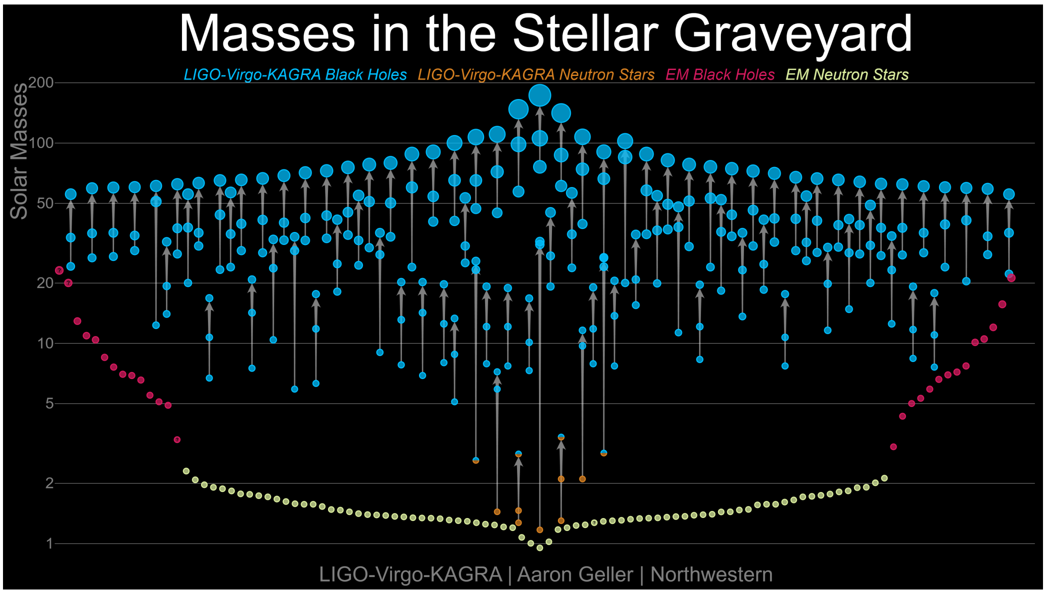

Figure 1.3: Black hole mergers detected via gravitational waves by the Ligo-Virgo collaboration as of Jan 2024.

and many more such events have now been detected.

1.2 Useful Astronomical Units

1.2.1 Distances

- Radius of Earth's orbit around the Sun ≡ 1 Astronomical Unit (AU) $= 1.5 \times 10^{13}$ cm
- Distance at which 1 AU subtends an angle of 1 second of arc (see Fig-

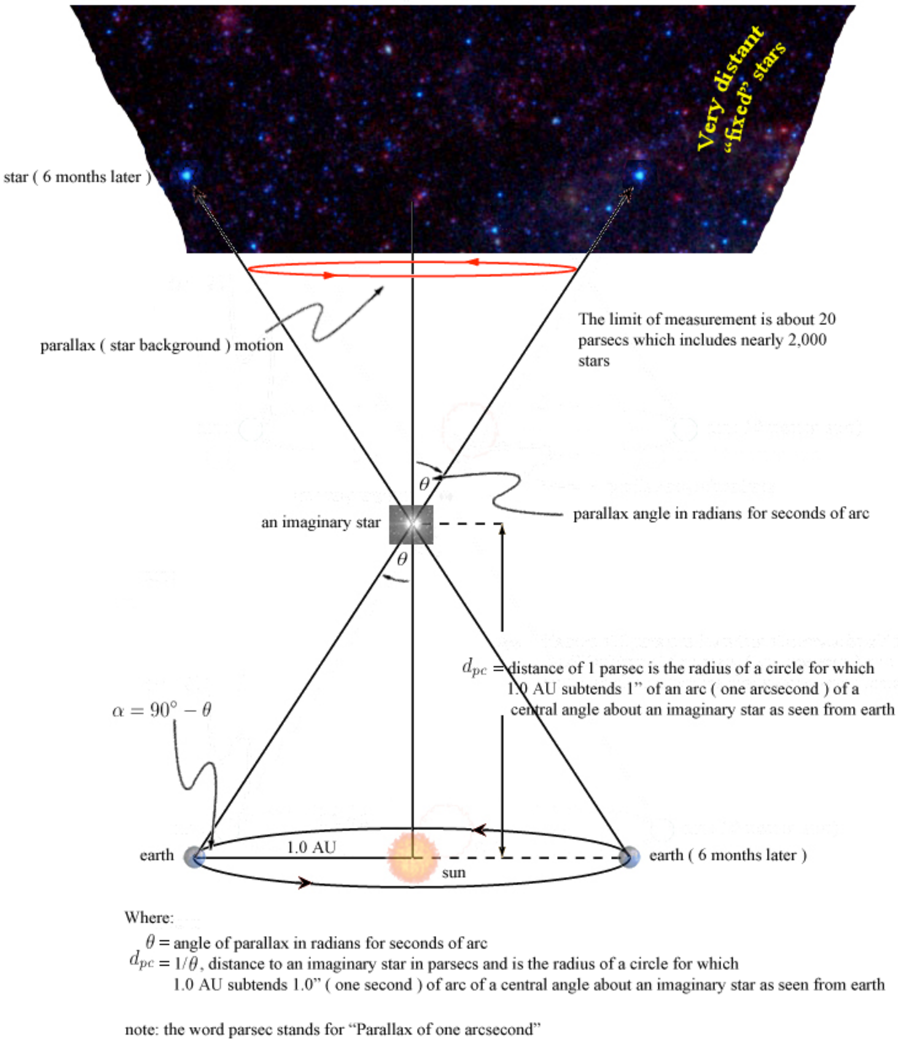

Figure 1.4: Parallax. When the angle θ subtended by a nearby star is 1 arcsec, the star is at a distance of 1 parsec.

ure 1.4):

$$\frac{1.5 \times 10^{13} \times 360 \times 60 \times 60}{2\pi} = 3.1 \times 10^{18}\,\text{cm} \equiv \boxed{1\,\text{parsec}} \tag{1.1}$$

- pc, kpc, Mpc are the most commonly used distance units in astronomy, e.g.:
- 1.3 pc = distance from the Sun to the nearest star (Proxima Centauri)
- 8.5 kpc = distance from the Sun to the Galactic Centre
- 1 Mpc = size of the Local group of galaxies
- 20 Mpc = distance to the Virgo cluster of galaxies
- 4300 Mpc = Hubble radius (radius of the observable universe) $= c/H_0$, where H_0 is the value of the Hubble constant today $= 70\,\text{km s}^{-1}\,\text{Mpc}^{-1}$

Figure 1.5: The nearby galaxy NGC 6744 observed with the Wide Field Imager on the MPG/ESO 2.2-metre telescope at La Silla. This large spiral galaxy is similar to the Milky Way and is at a distance of about 10 Mpc in the southern constellation of Pavo (The Peacock).

1.2.2 Masses

- 1 solar mass ($1\,M_\odot$) $= 2 \times 10^{33}$ g
- Stellar mass of the Milky Way $\simeq 1 \times 10^{11}\,M_\odot$

1.2.3 Luminosity and Magnitudes

Astronomers measure the brightness of celestial objects on a log scale which goes backwards!

$$F_1/F_2 = 10^{0.4(m_2 - m_1)} \quad (1.2)$$

where F are the fluxes and m the *apparent magnitudes.* We define flux as the energy that passes per unit time through a unit area (so, for example, the energy per unit time, or the power, collected by a telescope of area T is just $F \times T$). The luminosity is the total power emitted by a source,

$L = 4\pi d^2 F$, where d is the distance, assuming that the source radiates isotropically. This assumption is generally a good approximation for stars, but breaks down dramatically for sources of beamed radiation, such as γ-ray bursts.

Magnitudes and luminosities are usually measured over a range of wavelengths (see Lecture 2). Note that:

- $\Delta m = +0.75 \rightarrow (F_1/F_2) = 2$
- $\Delta m = +1 \rightarrow (F_1/F_2) = 2.5$
- $\Delta m = +2.5 \rightarrow (F_1/F_2) = 10$
- $\Delta m = +5 \rightarrow (F_1/F_2) = 100$

The *absolute magnitude* M of an object is the magnitude that object would have if placed at a distance of 10 pc, from which we define a *distance modulus* (in magnitudes)

$$m - M = 2.5\log(d/10)^2 = 5\log(d/10) = 5\log d - 5 \qquad (1.3)$$

where d is the distance in parsec.

Distances, and therefore absolute magnitudes, are notoriously difficult to measure in astronomy.

1.3 What is a Star?

A useful definition of a star is an object in which nuclear reactions are (or have been) sufficient to balance surface radiation losses.

1.3.1 The birth of stars

We can understand better this definition in the context of our broad picture of stellar formation and evolution. The starting point is when a cloud of cold, molecular gas is pushed out of equilibrium by some physical process (e.g. a passing shock wave). As the cloud collapses under its own gravity, gravitational potential energy is turned into kinetic energy of its particles (i.e. heat). As a result the temperature and density of the cloud increase as it collapses. Once the temperature of the cloud core reaches sufficiently high values, in excess of several million degrees, nuclear fusion can begin, converting hydrogen into helium. Thermonuclear reactions now provide a non-gravitational source of energy, whose heating can supply the pressure required to support the gas against further collapse: a star is born!

1.3.2 The death of stars

Nuclear fusion is exothermic because the rest mass of a He nucleus is less than the sum of the rest masses of two neutron and two protons. This mass defect, corresponding to an energy $E = mc^2 = 26\,\mathrm{MeV}$ which is the binding energy of the He nucleus, is released during nuclear fusion as kinetic energy into the surrounding gas. Thermonuclear reactions can proceed in the interior of stars fusing lighter elements into heavier ones up to and including Fe. However, elements heavier than Fe have a *lower* binding energy per nucleon than Fe—that is, energy has to be supplied, rather than extracted from the system in order to produce elements heavier

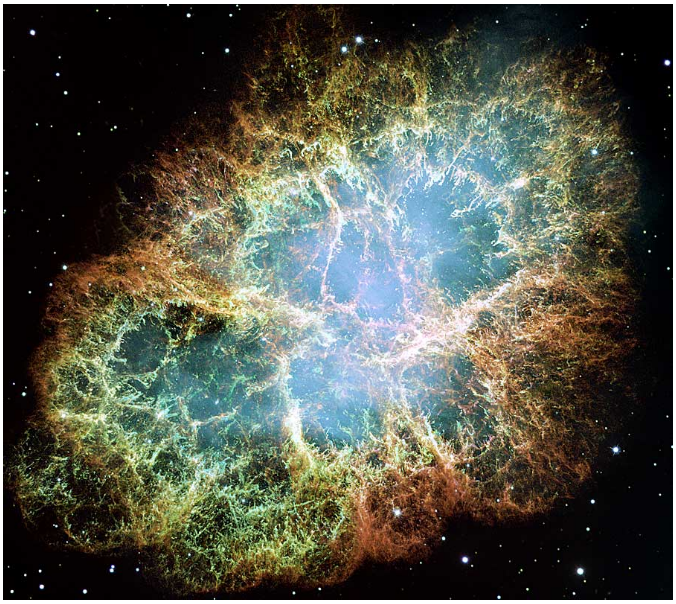

Figure 1.6: *Hubble Space Telescope* image of the Crab Nebula, the remnant of a massive star that exploded as a Type II supernova in 1054 A.D. The nebula is $\sim 2\,\mathrm{kpc}$ from the Sun, in the constellation of Taurus. The ejected gas is still moving outwards with speeds of $\sim 1500\,\mathrm{km\ s^{-1}}$. At the centre of the nebula lies the Crab Pulsar, a rapidly spinning neutron star.

than Fe by nuclear fusion.

Thus, when a star has developed an iron core, it can no longer supply the pressure to balance the inward pull of gravity. Most stars end their lives by ejecting their outer layers, either in supernova explosions (see Figure 1.6), or in less energetic mass loss events such as planetary nebulae (see Figure 1.7).

1.4 Galactic Chemical Evolution

In either case, some fraction of the elements synthesised in the stellar interior during the life of the star and in the supernova explosion which marked its death is returned to the interstellar medium where it will be

Figure 1.7: *Hubble Space Telescope* image of the Helix Nebula, the prototypical and closest planetary nebula, at a distance of only $\sim 200\,\mathrm{pc}$. The nebula consists of the outer layers of a solar-mass star, expelled towards the end of its life and made to glow by the ultraviolet light emitted by the hot core left behind (visible at the centre of the nebula). The expansion velocity is $\sim 20\,\mathrm{km\ s^{-1}}$. The core, with a mass of $\sim 0.6 M_{\odot}$, will eventually become a white dwarf. Our own Sun may well turn into a planetary nebula in about five billion years.

available for subsequent cycles of star formation. To our knowledge, all the elements of the Periodic Table—including those so central to life as we know it— were manufactured in the interiors of stars. The only exception are the light elements created by Big Bang nucleosynthesis in the first three minutes or so of the existence of our Universe: H, He, Li and some of their isotopes. For convenience, astronomers refer to all elements heavier than Li as 'metals', to indicate elements created by stellar, rather than primordial, nucleosynthesis.

There is thus a cycle of Galactic chemical evolution and indeed of 'Cosmic' chemical evolution when we consider the Universe as a whole. Presumably the gas in our Galaxy initially had a very small fraction of 'metals' which increased over the last 13 billion years or so with the progress of star formation. When we look at a recent region of star formation, such as the Orion nebula, we find the following composition, by mass:

Hydrogen = X = 0.7392
Helium = Y = 0.2486
Everything Else = Z = 0.0122.

Thus, the cumulative effect of all the previous star formation activity in the Milky Way Galaxy—where 80-90% of the baryonic mass is in stars and 10-20% is in gas—has been to enrich the interstellar medium to just over 1% of the mass in metals.

1.4.1 Stellar populations

When we consider the stars in our Galaxy, we find distinct populations, with different kinematics, ages, and metallicities (see Figure 1.8):

- **The disk**. It contains most of the stellar mass of the Milky Way: $M_{\rm disk} = (5 \pm 1) \times 10^{10} M_\odot$. Rotationally supported: at the location of the Sun, $v_{\rm rot} = 220\,{\rm km\ s^{-1}}$. Metal-rich: $Z \simeq 0.2$–$1.5 Z_\odot$. Young stars are found here; current star-formation rate: ${\rm SFR} \simeq 1.7 M_\odot\ {\rm yr}^{-1}$.
- **The bulge**. $M_{\rm bulge} = (0.9 \pm 0.1) \times 10^{10} M_\odot$. The disk is not uniformly thick. Near the centre, there is a thicker, roughly spherical region that has different properties from the rest of the disk. In contains a mix of stars, some recently formed and some old, as well as a supermassive black

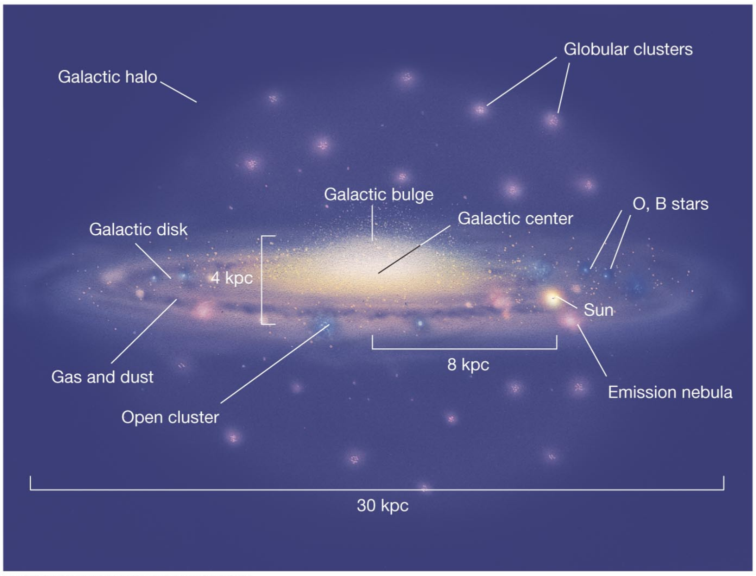

Figure 1.8: Schematic representation of the stellar populations of our Galaxy.

hole ($M_{\rm bh} \simeq 4.1 \times 10^6 M_\odot$).

- **The halo**. $M_{\rm halo} \simeq 1 \times 10^9 M_\odot$. Kinematics are dispersion dominated. Contains some of the oldest objects in the Universe, the Globular Clusters, and some of the most metal-poor stars known, some with less than 10^{-5} the amount of metals (Fe) present in the interstellar gas today. (Partly) made up of the remnants of previous merger events.

The properties of these different stellar populations give us clues to the processes that led to the formation and evolution of our Galaxy.