Basic Astrophysics - Summary

by Dr. Helga Dénes (hdenes@yachaytech.edu.ec)

This summary is based on the book Chapters 1 from Arnab Rai Choudhuri: Astrophysics for physicists.

1 Units

For mass measurements **Solar mass** (the mass of the Sun) is used most often: $M_\odot$
$M_\odot = 1.99 \times 10^{30}$ kg.

The average distance of the Earth from the Sun is called the **Astronomical Unit** (AU). Its value is: AU $= 1.50 \times 10^{10}$ m.

As the Earth goes around the Sun, the nearby stars seem to change their positions very slightly with respect to the faraway stars. This phenomenon is known as **parallax**.

The **parsec** (pc) is the distance where the star has to be so that its **parallax** turns out to be 1". (1" is equal to $\pi/(180 \times 60 \times 60)$ radians) pc $= 3.09 \times 10^{16}$ m.
1 pc is equal to 3.26 light years (not used much in astronomy). For even larger distances, the standard units are kiloparsec (103 pc, kpc), megaparsec (106 pc, Mpc) and gigaparsec (109 pc, Gpc).

Astrophysicists use years for large time scales and seconds for small time scales, the conversion factor being yr $= 3.16 \times 10^7$ s. gigayear (109 yr, Gyr) is often used

Equatorial coordinate system:
- **Declination** (δ) - latitude
- **Right ascension** (R.A.) - longitude

The points where the Earth's rotation axis would pierce the celestial sphere are called **celestial poles**. The great circle on the celestial sphere vertically above the Earth's equator is called the **celestial equator**.

Since the Earth goes around the Sun in a year, the Sun's position with respect to the distant stars, as seen by us, keeps changing and traces out a great circle in the sky. The **ecliptic** is this great circle.

Precession: Earth's rotation axis is not fixed, but precesses around an axis perpendicular to the plane of the Earth's orbit around the Sun. This means that the celestial pole traces out an approximate circle in the celestial sphere slowly in about 25800 years, around the pole of the ecliptic.

Galactic coordinates, widely used in galactic studies. In this system, the plane of our Galaxy is taken as the equator and the direction of the galactic centre as seen by us (in the constellation Sagittarius) is used to define the zero of longitude.
- Galactic longitude (l)
- Galactic latitude (b)

The magnitude scale for describing apparent brightnesses of celestial objects is a logarithmic scale. Stars in two successive classes should differ in apparent brightness by a factor $100^{1/5}$

$$\frac{l_2}{l_1} = 100^{1/5(m_1 - m_2)}$$

$$m_1 - m_2 = 2.5 log_{10} \frac{l_2}{l_1}$$

The definition of **apparent magnitude** denoted m, which is a measure of the apparent brightness of an object in the sky. Note that the magnitude scale is defined in such a fashion that a fainter object has a higher value of magnitude.
If we use apparent brightnesses based on the radiation in all wavelengths, then the magnitude defined from it is called the **bolometric magnitude**.
A system, called the Ultraviolet-Blue-Visual system or the **UBV system**. In this system, the light from a star is made to pass through **filters** which allow only light in narrow wavelength bands around the three wavelengths: 3650Å, 4400Åand 5500Å. From the measurements of the intensity of light that has passed through these filters, we get magnitudes in ultraviolet, blue and visual, usually denoted by U, B and V.

We can use (B - V) as an indication of a star's **colour**. The more reddish a star, the larger will be the value of (B - V).

The **absolute magnitude** of a celestial object is defined as the magnitude it would have if it were placed at a distance of 10 pc. This is often used to denote the intrinsic brightness of objects. The relation between relative magnitude m and absolute magnitude M:

$$m - M = 5log_{10}\frac{d}{10}$$

2 Sources of astronomical information

- Electromagnetic radiation
- Neutrinos
- Gravitational radiation
- Cosmic rays
- + more for planetary and solar system science (plasma probes, magnetometers, rock samples from the Moon and from asteroids, etc.)

2.1 Neutrinos

A Nuclear reactions inside stars produce neutrinos. Since neutrinos take part in weak interactions alone, most of the neutrinos created at the centre of a star can come out without interacting with the stellar matter. However, the very small crossection of interaction between matter and neutrinos also makes it difficult to detect neutrinos. Because of this difficulty of detecting neutrinos, we expect to detect neutrinos only either from very nearby sources or from sources which emit exceptionally large fluxes of neutrinos (like a supernova explosion, or blazars (a typo of extremely bright AGN)).

Detector types:
- Radiochemical methods (the neutrino triggers a chemical reaction, producing a radioactive element)
- Cherenkov detectors (the neutrino produces fast charged particles, if the speed of a charged particle is faster than the speed of light in the medium, then Cherenkov light gets emitted.)

For detecting neutrinos, we need a huge amount of some substance with atoms having nuclei with which neutrinos interact. Current day experiments: Super-K, LVD, IceCube, KamLAND, Borexino, Daya Bay, and HALO

2.2 Cosmic rays

Most common way of detection is vis Cherenkov radiation. When gamma rays reach the Earth's atmosphere they interact with it, producing **particle showers**. Nothing can travel faster than the speed of light in a vacuum, but light travels 0.03 percent slower in air. Thus, these ultra-high energy particles can travel faster than light in air, excite the air molecules and create a blue flash of **"Cherenkov light"** similar to the sonic boom created by an aircraft exceeding the speed of sound. This is the light that the telescopes detect.

Cherenkov radiation is electromagnetic radiation emitted when a charged particle (such as an electron) passes through a dielectric medium at a speed greater than the speed of propagation of light in that medium.

Telescopes: H.E.S.S., MAGIC and VERITAS), CTAO (Cherenkov Telescope Array Observatory)

2.3 Gravitational waves

Indirect detection with binary pulsars spiralling towards each other, because they are loosing energy due to gravitational radiation.
Direct detection by laser interferometry, e.g. LIGO and Virgo

LIGO is essentially a Michelson interferometer with two 4km long arms.

LIGO and Virgo have observed the merger of several compact object (black holes, neutron stars) binaries.

2.4 EM waves

The **atmospheric transmission** characterises how much radiation can reach the surface of the Earth at different wavelengths. Water vapour absorbs a large range of radiation. The ionosphere reflects certain radiation.

Telescopes observing at different wavelengths have different requirements:
- High mountains in dry places, to minimise water vapour
- Remote sights with no light or radio contamination
- In space

Two types of measurements:
- Imaging
- Spectroscopy

2.4.1 Optical astronomy

The **angular resolution** of a telescope is $\Theta = 1.22\frac{\lambda}{D}$, where λ (m) is the wavelength and D (m) is the diameter of the mirror of telescope. Note: This formula gives Θ in radians.

Currently the most advance telescopes have mirror sizes in the 10m range, however telescopes with even larger mirrors are in the construction.

Telescopes which are of this size and larger, however, produce images much less sharp than what is theoretically expected. This is because the air through which the light rays pass before reaching the telescope is always in **turbulent motion**. As a result, the paths of light rays become slightly deflected, giving rise to blurred images. The term **seeing** is used to indicate the quality of image under a given atmospheric conditions. Seeing is rarely good enough to allow images which are sharp enough to resolve more than 0.5".

Solutions:
- adaptive optics
- speckle imaging
- sending the telescope to space

It is clear that a bigger ground-based telescope cannot achieve higher resolutions beyond a certain limit. However, the light-gathering ability of a telescope depends on $D^2 \rightarrow$ larger telescopes can detect fainter objects.

The biggest observatories (best location) are high mountains close to the sea with stable airflow, e.g.:
- Atacama Desert, Chile
- Hawaii
- Canary Islands

2.4.2 Radio

The resolution of a telescope depends on its size and the wavelength of light that is getting observed. Since radio waves have very long wavelengths, this corresponds to needing much larger telescopes compared to optical telescopes. However, we can use interferometry to dramatically improve the resolution of telescopes. In this case the "diamtere" in the resolution formula is replaced with the **"baseline"**, which is the distance between the individual telescopes. The highest angular resolution images to date have been taken with radio telescopes.

Types of telescopes:
- single dish telescopes (or single antenna), can have diamteres up to 100 - 500 m.
- interferometres (a combination of several antennas), can have baselines up to several thousands of km.

2.4.3 Infrared

- Telescopes on high mountains can observe in the near-infrared, e.g. VISTA, UKIRT etc.
- Observatories on airplanes: e.g. SOFIA, Galileo Observatory, Kuiper Airborne observatory
- Space observatories: Spitzer, AKARI, Herschel observatory, James Webb Space Telescope (JWST), WISE
- Difficulty: most telescopes require cryostatic cooling (e.g. liquid nitrogen cooling)
- Sources: interstellar dust, old stars, supernova remnants

2.4.4 UV

- Sources: very young massive stars and some very old stars, galaxies that contain young massive stars, the Sun
- Some UV radiation can be observed from the surface of Earth, but most observatories are in space, such as: the Hubble Space Telescope, the GALEX telescope, the FUSE telescope

2.4.5 X-ray

- Only detectable above the atmosphere: balloon experiments and satellites
- X-rays are reflected from metal surfaces only when they are incident at grazing angles (otherwise, they pass through metals). Hence X-ray telescopes are designed very differently from optical telescopes.
- Also, mirrors in X-ray telescopes have to be much smoother than mirrors in optical telescopes because of the small wavelength of X-rays.
- Examples: ROSAT, Chandra, XMM-Newton
- Sources: hot plasma (millions of K) Examples: the Sun, Supernova remnants, intra cluster matter in galaxy clusters, AGN, accreting binary stars, neutron star or black hole binaries.

2.4.6 γ-ray

- Radiation above a 100 keV (from high energy sources)
- Sources: solar flares, supernovae, hypernovae, pulsars, blazars (AGN with the jet pointing towards Earth), thunderstorms on Earth, etc.
- Gamma-ray telescopes (satellites): INTEGRAL, Fermi, Egret, AGILE, etc.
- Indirect detection trough particle showers in the atmosphere (see cosmic ray section)