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PHYC30019 Astrophysics

Course Summary

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0 Introduction

0.1 Housekeeping

0.1.1 Texts and References

- Maoz - Astrophysics in a Nutshell (free download apparently)

0.1.2 Marking system

- $3 \times 10\%$ workshops Weeks 4, 8 and 11
- 70% exam

0.2 Definitions

0.2.1 Astronomy

- Colects photons
- Some branches (small at current) investigates cosmic rays
- Some investigate gravitational waves
- Measured quantities for photons:
  - 2 anguar dimensions
  - Spectrum
  - Luminosity (distance)
  - Flux (amount)
- Objects investigated:
  - Planets, asteroids, comets (not investigated in class
  - stars, globular clusters, galaxies, gas clouds, clusters of galaxies, superclusters, active galactic nuclei

0.2.2 Astrophysics

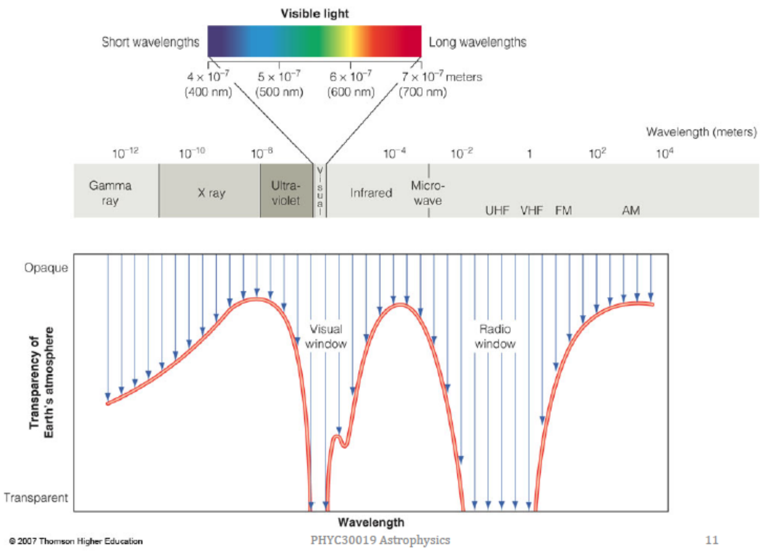
- Applies physics and mathematics to understand the universe and its components (formation, structure, evolution, dstribution)
- Uses many branches of physics and maths
- Often things are measured imprecisely (order of magnitude)
- Computational processes are used (some high precision measurements are taken, e.g. for pulsars)
- Types of radiation processes:
  - thermal (emijng a blackbody), synchrotron, bremsstrahlung, Compton, inverse Compton

0.3 Photons

- Can be defined by frequency $c = \lambda\nu$
- Or energy $E = h\nu$
- Or temperature $E = kT$

Radiation	Wavelength	Frequency (Hz)	Energy/ photon (J)	Temperature (K)
Gamma rays	<0.01nm	>3x10^{19}	>2x10^{-14}	<10^{9}
X-rays	0.01 -10nm	3x10^{19}-3x10^{16}	2x10^{-14}-2x10^{-17}	10^{9}-10^{6}
Ultraviolet	10-300nm	3x10^{16}-10^{15}	2x10^{-17}-7x10^{-19}	10^{6}-5x10^{4}
Optical	300-700nm	10^{15}-4x10^{14}	7x10^{-19}-3x10^{-19}	5x10^{4}-2x10^{4}
Infrared	700nm-1mm	4x10^{14}-3x10^{11}	3x10^{-19}-2x10^{-22}	2x10^{4}-10
Microwave	1mm-1cm	3x10^{11}-3x10^{10}	2x10^{-22}-2x10^{-23}	10-1
Radio	1cm-30m	3x10^{10}-10^{7}	2x10^{-23}-7x10^{-27}	1-5x10^{-4}

- Some wavelengths have more attenuation (decay) than others (see figure below)



0.3.1 Characteristic scales

- Cosmological
  - Scale of observable universe (light travelling over fininte universe lifetime) c/H_0
  - H_0 is Hubble constant
- Parsec
  - $1\text{pc} = 3.1 \times 10^{18}\text{cm} = 3.3\text{ly}$
  - Defined based on universe size
  - Distance at which 1AU (distance to Sun) substends by an angle of one arcsecond

0.3.2 Copernican Principle

- We are not in a favoured position in the universe.
- Local physics is the same as distant physics
- Thus we rarely use "new" physics; exceptions are dark mater and dark energy

0.3.3 Cosmological Principle

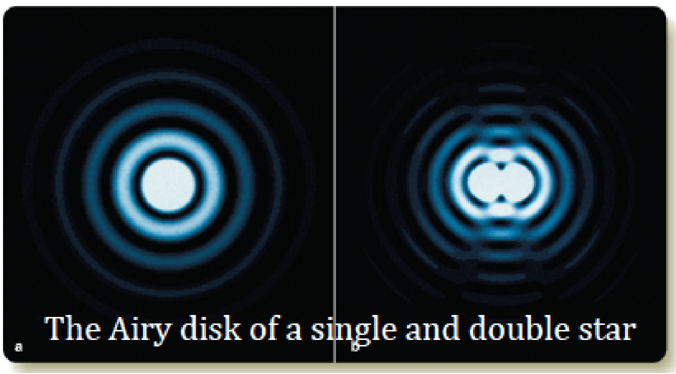
- On average, the universe is homogeneous and isotropic at any time in its evolution
- Local measurements of isotropy and homogeny + Coperican principle imply the Cosmological principle
- Universe is homogenous to about 1% on a scale of 100Mpc
- We need to average over a large area to get this homogeny
- Isotropic = rotational invariant

0.4 Astronomical Observing

Four important dimensions to measure:

0.4.1 Angular resolution

- Smallest angle on the sky between two sources that telescopes can separate
- Point source produces diffraction pattern with central spot of radius $\theta = 1.22\lambda/D$
- D =diameter of aperture (known as Airy disk)



0.4.2 Ligth-gathering power

- Larger area = more photons collected
- ILimited by ability to make large glass that doesn't deform

0.5 Integration time

- More sensitive if more pghotons are collected
- Hence, observe for longer
- Try to have minimal noise

0.5.1 Wavelength range

- Different telescopes observe different wavelengths
- Not all photons reach the Earth, so we have outer space telescopes

0.6 The Big Questions

- How did the universe begin and how will it evolve? – the behaviour of matter, energy, space and time
- What is the nature of the stuff the universe is made of?
- Physics in extreme physical environments: how does matter behave?
- How did the universe we inhabit form - stars, galaxies and planets?
- Are we alone: what do other planetary systems look like? i what is life?

1 Blackbody Emission

- We approximate a lot of things as blackbodies
- We assume we can model things by blackbody spectrums

$$u_\nu = \frac{8\pi\nu^2}{c^3}\frac{h\nu}{e^{h\nu/kT}-1} \tag{1}$$

- The blackbody spectrum is the energy density u_ν
- Units: erg cm$^{-3]}$ Hz^{-1}.
- Flow of energy I_ν; derivative of the energy density w.r.t solid angle and multiplying by c
- = energy passing through unit area per unit time

$$\begin{aligned} I_\nu &= c\frac{du_\nu}{d\Omega} = c\frac{u_\nu}{4\pi} && (2)\\ &= \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1} && (3)\\ &= B_\nu && (4) \end{aligned}$$

- Called B_ν because blackbody
- Flow of energy in a particular direction inside a BB is the intensity I_ν
- Related to outgoing flux by $df_\nu = I_\nu \cos\theta d\Omega$

Okay, I'll just try to summarize stuff as I go along. Very little on written on the board, at the moment.

- Flux we observe depends on luminosity and distance from star ($f_\nu = \frac{L_\nu}{4\pi^2}$)
- Luminosity given by $L_\lambda d\lambda = 4\pi^2 R^2 B_\lambda d\lambda$
- Inverse square law:

$$\frac{f_1}{f_2} = \frac{d_2^2}{d_1^2} \tag{5}$$

1.1 Limiting Blackbody Spectra

At low frequencies,

$$\begin{aligned} h\nu &\approx kT\\ B_\nu &\sim \frac{2\nu^2}{c^2}kT \end{aligned}$$

At high frequencies,

$$\begin{aligned} h\nu &\approx kT\\ B_\nu &\sim e^{-(h\nu/kT)} \end{aligned}$$

2 Stars: Observations

2.1 Stellar Attributes

- Distance
- Temperatures
- Luminosity
- Radius
- Mass

2.2 Distance

Parallex, arcsecond, parsec.
The Moon is 30 arcminutes across.
Distance from Earth to Sun = 1AU.

$$d = \frac{1AU}{\tan(\alpha)} \approx \alpha^{-1} AU \tag{6}$$

For small angles (and most stars have very small angles to us) we can use the small angle approximation

$$\tan\theta = \theta + O(\theta^3) \tag{7}$$

2.3 Temperature

Photon random walks its way out of a star (interacting with electrons). Could take ∼3 seconds to get out straight, but actually takes thousands of years.
The photosphere is the point where star density is low so a photon can escape without interacting. This is the "surface".

2.3.1 Brightness temperature

Temperature measured at a particular frequency (equivalent temperature for a BB to generate that frequency)

2.3.2 Colour temperature

Planck spectrum is fitted to spectrum.
The colour of a star is the ratio of two different wavebands.

2.3.3 Effective temperature

By using

$$L = 4\pi r^2 \sigma T^4 \tag{8}$$

We can measure luminosity, if we know the radius we can find temperature.

2.4 Magnitudes

Definition of apparent magnitude:

$$m_\lambda = -2.5 \log_{10} f_\lambda + C \tag{9}$$

Mimics the human eye (which views things logarithmically). Colours are defined as the difference between magnitudes. UBV system = Ultraviolet, Blue, Visual.

$$B - V = m_B - m_V \tag{10}$$

More B = bluer. NOTE: independent of distances (they cancel out b/c logarithic difference).

2.5 Luminosity

Determined after finding distance d and flux f. Usually diefined in a waveband.

$$L = 4\pi d^2 f \tag{11}$$

Integrating over all wavelengths gives bolometric luminosity.

2.6 Radius

Difficult to measure stellar radi (because they're too far away); often use indirect measurements. Can also use occultation, interferometry and eclipsing binaries. Indirect way:

$$L = 4\pi r^2 \sigma T^4 \tag{12}$$

Only ~100 stars with known radii. Betelguese is the only star (apart from the Sun) with a directly measured radius; 0.125 arcsec. Recent data gives mass-radius relationship for low-mass stars as basically linear.

3 Stars: Observation II

3.1 Mass

To first order, the mass of a star tells you what sort of star you are looking at. Mass measurements are often used by binary systems

- Visual binary: two stars resolved implies long orbital timescales, so it takes a long time to get any information
- Astrometric binary: cannot resolve smaller object, so we observe orbital motion of brighter star; a "wobbling" orbit of a bright object implies there is another massive object there (this is how some exoplanets have been discovered)
- Eclipsing binary: orbital plane of binary is in line of sight; we measure parameters of an eclipse (most planets have been discovered using this)
- Spectroscopic binary: absorption or emission lines of both objects are observed in spectrum. Absorption lines will move with respect to each other (cannot resolve both stars, but can deduce the existence of a binary system)

We can investigate the curvature of an object in spacetime to determine mass, however this is a small perturbation so we often use other ways to determine mass.

3.1.1 Key attributes of a binary

The two stars orbit a common centre of mass; bigger object will be closer to the centre of mass.

$$r_1 M_1 = r_2 M_2 \tag{13}$$

Kepler's 3 laws:

1. Both orbits are similar ellipses
2. Orbiting system conserves angular momentum; travels slower when further away etc.
3. When τ = period, ω = angular frequency, a = semi-major axis, M = masses, we have the equation:

$$\tau^2 = \frac{(2\pi)^2}{\omega^2} = \frac{a^3}{G(M_1 + M_2)} \tag{14}$$

3.1.2 Mass measurement

Assuming circular orbits (not elliptical),

$$\begin{aligned}
\text{Centre of mass: } & r_1 M_1 = r_2 M_2 \\
& a = r_1 + r_2 \\
\text{Equation of motion: } & M_1 \omega^2 r_1 \frac{G M_1 M_2}{a^2} \\
& v_{1obs} = \langle v_1 \rangle \sin(i) \\
\text{Projected velocities: } & v_{2obs} = \langle v_2 \rangle \sin(i) \\
\text{Final equation: } & (M_1 + M_2) \sin^3(i) = \frac{\tau(\langle v_{1obs} \rangle + \langle v_{2obs} \rangle)^3}{2\pi G}
\end{aligned}$$

Note: i = angle between plane of motion and line-of-sight. We get the final equation using Kepler 3.

In a visual binary, if the period is 'short', then the angular radii can be directly measured $\Rightarrow$ the ratio of masses. Kepler's 3rd Law then gives the individual masses.

In a spectroscopic binary, we only measure the projected velocities, and so can only determine the sum of the masses up to a factor of $\sin^3(i)$.

When one of the stars has a much smaller mass, the equations can simplify.

Can use Doppler velocity of star with orbiting planet to measure planet mass (sensitive to a couple of metres, can determine mass of at lightest M_{Jupiter}).

3.1.3 Two monotonic empicial relationships

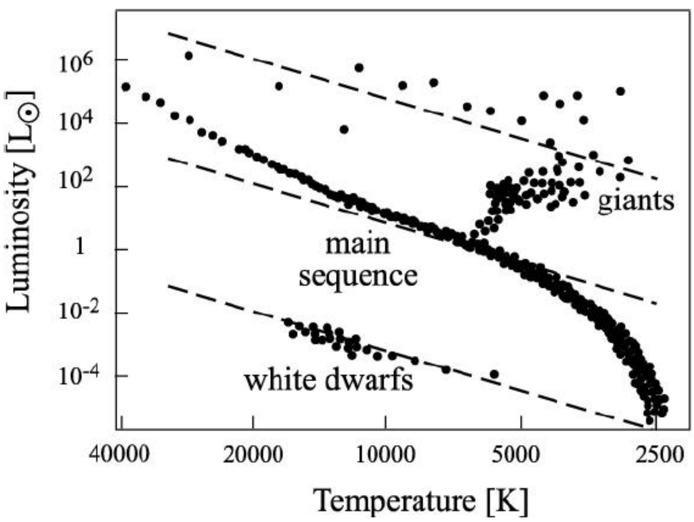
1. Mass-luminosity relationship:

$$\frac{L}{L_\odot} = 0.35\left(\frac{M}{M_\odot}\right)^{2.62} \qquad M < 0.7M_\odot$$
$$\frac{L}{L_\odot} = 1.02\left(\frac{M}{M_\odot}\right)^{3.92} \qquad M > 0.7M_\odot$$

   This implies more massive stars are much more luminous and 'burn' faster.

2. Hertzsprung-Russel Diagram

This is the diagram that pllots luminosity against temperature; see figure below.



3.2 Stellar Spectral Type

Stars can be divided into classes based on characteristics.

Spectral Class	Colour	B-V index	Temperature (K)		Examples
O	Blue-violet	-.035	28-50,000	ionised He	Naos, Mitaka
B	Blue-white	-0.16	10-28,000	neutral He, some H	Spica, Rigel
A	White	+0.13	7.5-10,000	strong H, some ionised metals	Sirius, Vega
F	Yellow-white	+0.42	6-7,500	H and ionised Ca & Fe	Canopus
G	Yellow	+0.70	5-6,000	ionised Ca, neutral metals	Sun
K	Orange	+1.2	3.5-5,000	neutral metals	Arcturus
M	Red-orange	+1.2	2.5-3,500	strong TiO bands	Betelguese