Astronomy & Astrophysics

MODULE 1 - Basics of Astronomy

DSE B1

2020

Sourav Mitra, Surendranath College

Syllabus

DSE B1 (a)

5.5 Astronomy and Astrophysics (Theory)

Paper: PHS-A-DSE-A2-TH	Credits: 5 (+1 for Tutorial)

1. Tools of Astronomy **15 Lectures**

(a) Contents of our Universe: basic introduction of stars, galaxies, clusters, interstellar medium, black holes, our own galaxy Milky Way.

(b) Mass, length, time and magnitude scales in astronomy.

(c) Interaction of light and matter fundamentals of radiative transfer (emission, absorption, radiative transfer equation, mean free path, optical depth), thermal radiation and thermodynamic equilibrium (Kirchhoff's law of thermal emission, Boltzmann and Saha equation, thermodynamics of black body radiation, concept of local thermodynamic equilibrium.

(d) Observational tools for multi-wavelength astronomy - telescope as a camera, optical telescopes (refracting and refrecting telescopes), radio telescopes, astronomical instruments and detectors, observations at other wavelengths (infrared, ultraviolet, X-ray and Gamma ray astronomy), all-sky surveys.

2. Stars and stellar systems **25 Lectures**

(a) Properties of stars (distance, brightness, size, mass, temperature, luminosity).

(b) Measurement of stellar parameters: distance parallax, Cepheid variables, nova and supernovae, red shift), stellar spectra, spectral lines, the Hertzsprung-Russell diagram, luminosity and radius, binary system and mass determination, scaling relation on the Main Sequence.

(c) Basic equation of stellar structure hydrostatic equilibrium and the virial theorem, radiative and convective energy transport inside stars, nuclear energy production. Equation of state, opacity, Derivation of scaling relations.

(d) Formation and evolution of stars star formation, pre-main-sequence collapse (gravitational instability and mass scales, collapse of spherical cloud, contraction onto the Main Sequence, Brown Dwarfs), evolution of high-mass and low-mass stars (core and shell hydrogen burning, helium ignition), late-stage evolution of stars, evolution of Sun-like stars and solar system.

(e) End stages of stars white dwarfs (electron-degeneracy pressure, mass-radius relation), neutron stars (mass limit of neutron stars, neutron stars observable as pulsars), black holes as end point of stellar evolution, supernovae.

3. Galaxies and the Universe **10 Lectures**

(a) Milky Way galaxy: components, morphology and kinematics of the Milky way, the galactic center, spiral arms.

(b) Classification and morphology of galaxies - quiet and active galaxies, types of active galaxies, Active Galactic Nuclei (AGN) and Quasars, accretion by supermassive black holes.

4. Cosmology **25 Lectures**

(a) Newtonian cosmology, Olber's paradox, Hubble's law and the expanding Universe, scale factor and comoving coordinate.

(b) Standard cosmology, the Friedmann equations from Newtonian cosmology, fluid equation , equation of state for matter, dust etc. from basic thermodynamics, cosmological redshift, dark matter, dark energy and the accelerating universe, tests and probes of Big Bang cosmology (the Cosmic Microwave Background, primordial nucleosynthesis).

Tutorial: In tutorial section, problems in the theory classes should be discussed. Problems and solutions regarding the theory course may be discussed.

Reference Books

1. An Introduction to Modern Astrophysics, B.W. Carroll & D.A. Ostlie, Addison-Wesley Publishing Co
2. Introductory Astronomy and Astrophysics, M. Zeilik and S.A. Gregory, 4 th Edition, Saunders College Publishing
3. Astrophysics in a Nutshell (Basic Astrophysics), Dan Maoz, Princeton University Press
4. An Invitation to Astrophysics, T. Padmanabhan, World Scientic Publishing Co
5. Foundations of Astrophysics, Barbara Ryden and Bradley M. Peterson, Addison Wesley

Additional Reference Books

1. Astronomy and Astrophysics, A. B. Bhattacharya, S. Joardar, R. Bhattacharya, Overseas Press (India) Pvt. Ltd

2. Astrophysics for Physicists, Arnab Rai Choudhuri, Cambridge University Press
3. Introduction to Astronomy and Cosmology, Ian Morison, John Wiley & Sons Ltd
4. Theoretical Astrophysics, Volume III: Galaxies and Cosmology, T. Padmanabhan, Cambridge University Press

Introduction

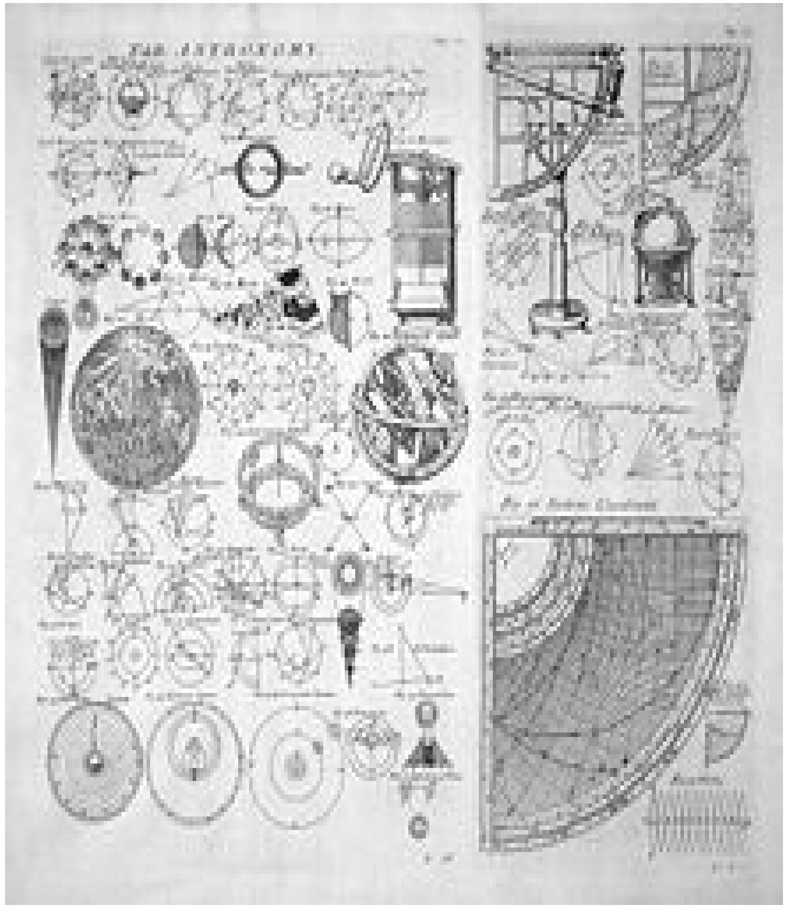
Introduction

Why study Astronomy & Astrophysics? Motivation

- **Oldest science** - navigation in sea and land using positions of stars in the sky - agriculture (season of harvest) - religious festivals depending on phases of moon and time of the year. Remember, there were no calendar - only by looking at the sky!

Although it originates from Astrology in the past, but the modern Astronomy is very different than Astrology. When people did not understand certain phenomena in the sky, some feared and some tried to understand it - astrology and astronomy diverge!

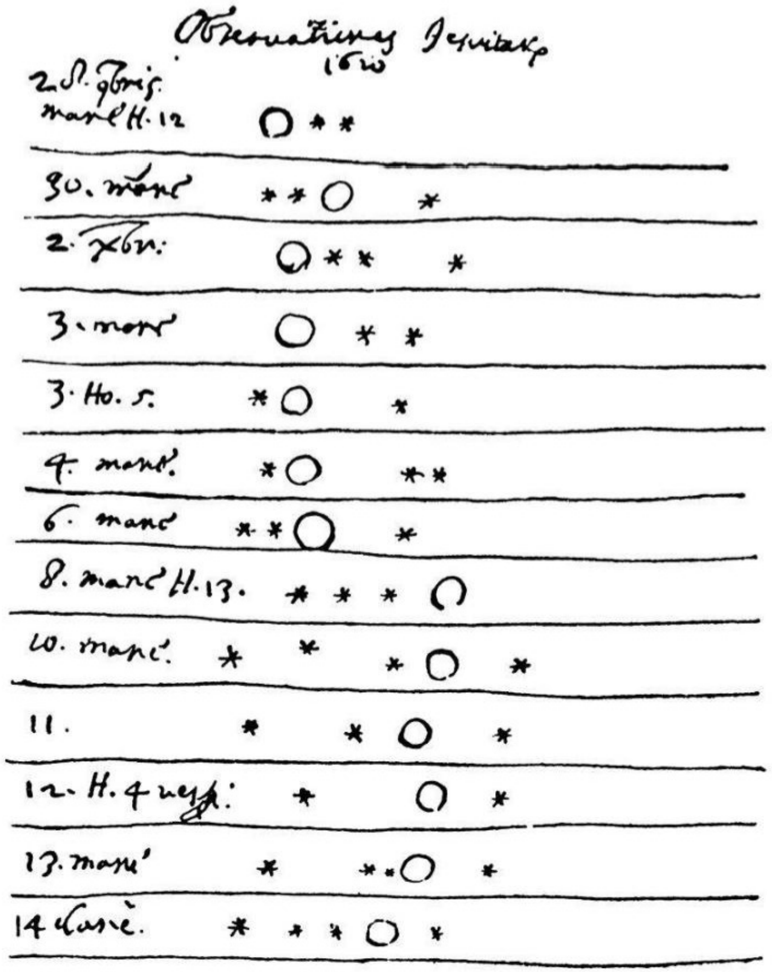
The science of Astronomy was all about figuring out when the next eclipse is going to happen or when do we expect a certain planet to be at a certain position of sky. Gradually with help of math and physics, Astronomy becomes Astrophysics!



Introduction

Why study Astronomy & Astrophysics? Motivation

From Galileo's book/diary (1610) - before that people believed things are imparfect only in Earth, the sky and outer space (heaven) are perfect! All the stars, Sun moves around us!



Galileo took his telescope and pointed at Jupiter (and 4 moons of it) - first time a telescope used by a scientist not by a sailor. He didn't know those are moons of Jupiter, he wrote them as stars. He realized that those things move around Jupiter like moon moves around us - First time something is discovered in the Universe that moves around other thing, other than Earth, before that people belived all things move around Earth ---- beginning of modern Astronomy!

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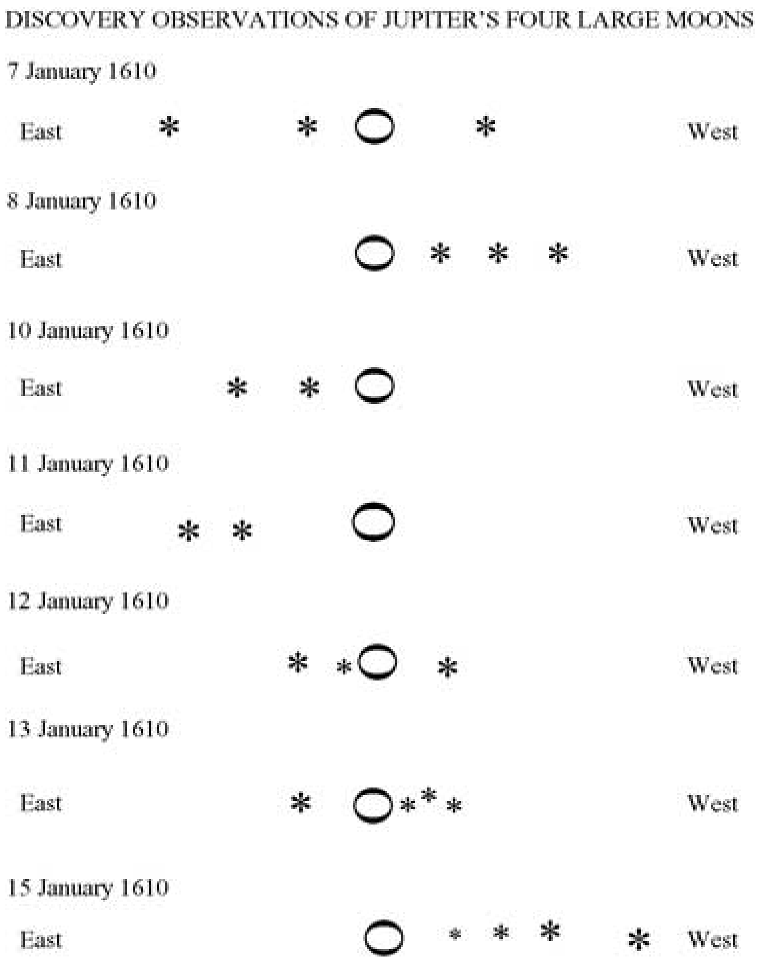

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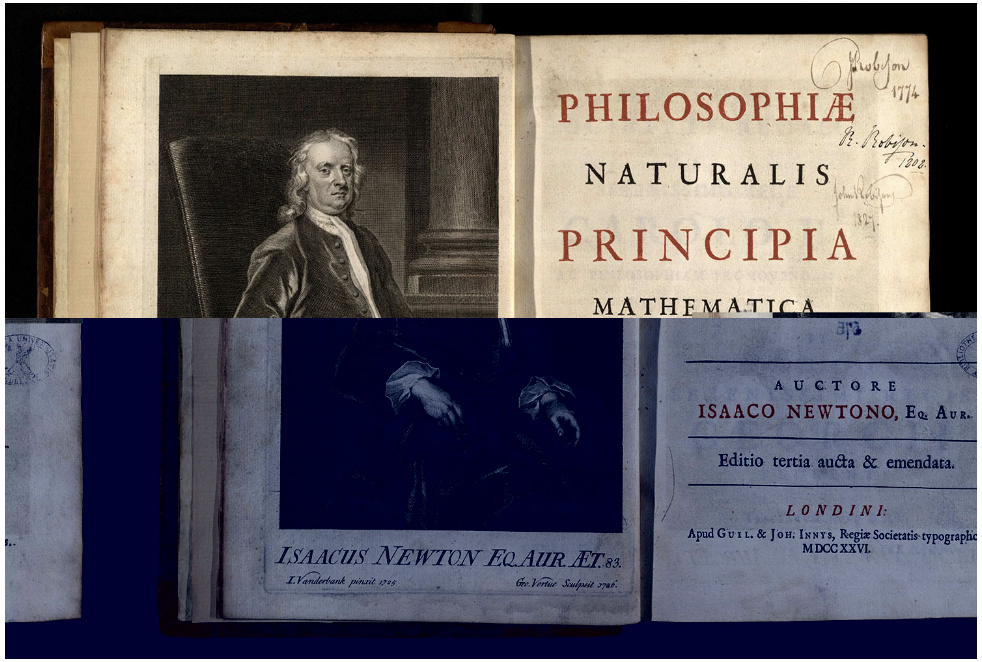
Why study Astronomy & Astrophysics? Motivation

The basic laws of Physics come from some basic Astronomical questions!



- ***Mathematical Principles of Natural Philosophy*** by **Isaac Newton (1687)** (A young faculty at Oxford named **Edmond Halley** came to him with a simple question - why does the commet keep coming back in every 75 years? Newton wrote down the classical laws of Physics and also laws of Gravitation to answer that in this book. **Keepler** had already written down some laws, but Newton established the mathematics behind that.)

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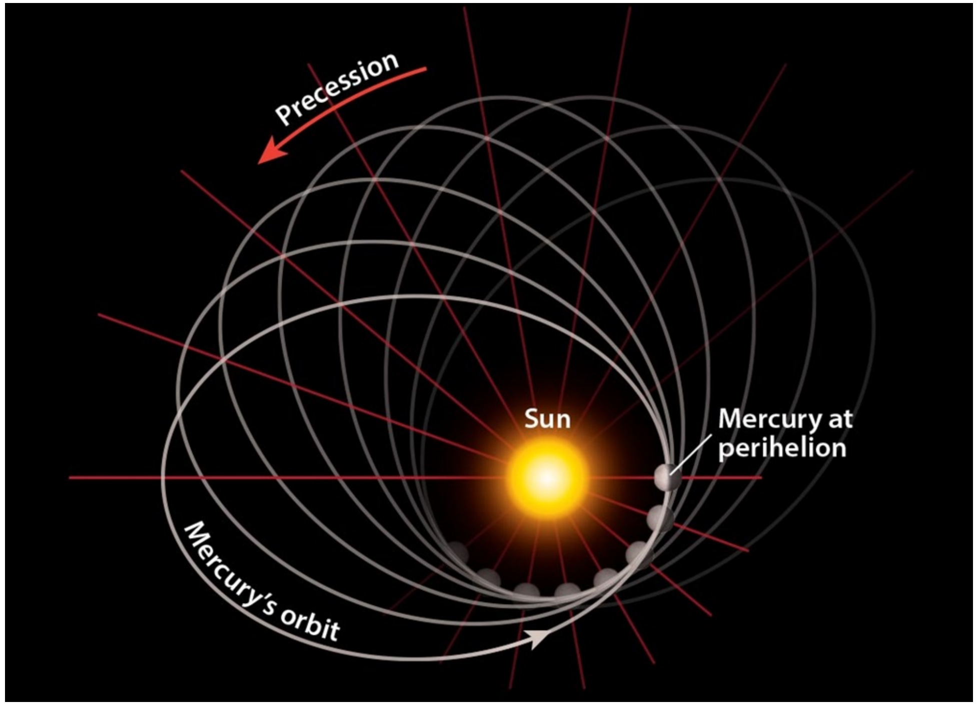
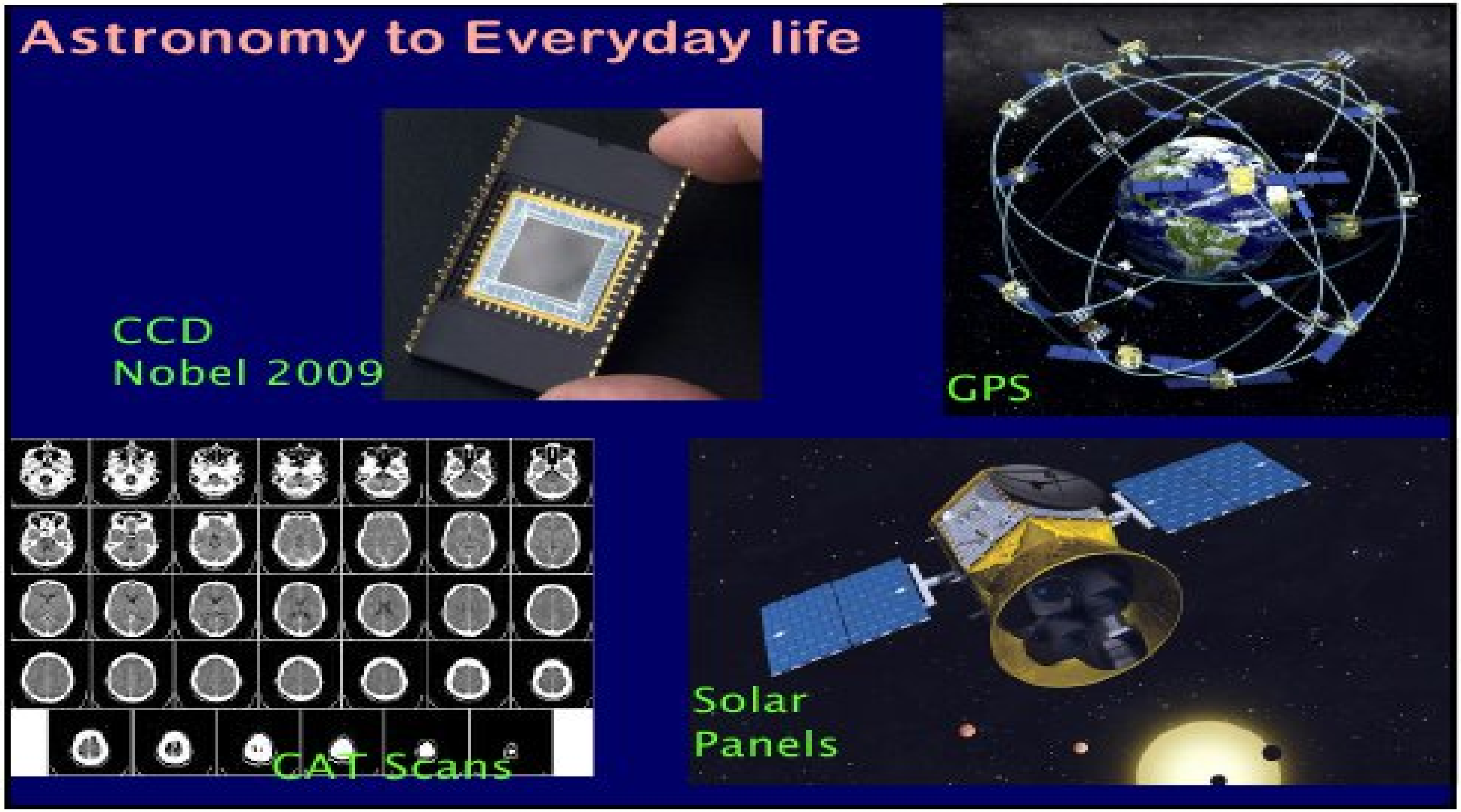
- **Light bending around star** (why Mercury's orbit around Sun has an anomaly?) --- **General Theory of Relativity** by **Albert Einstein (1915)**



Introduction

Why study Astronomy & Astrophysics? Motivation



First Digital camera was build so that we can mount it on a telescope in space and get better pictures!

Tools of Astronomy

Astronomical Scales

1. Astronomical Distances

Units of measurement of distances

- 1 **Astronomical Unit** (AU) is the mean distance between the Sun and the Earth.

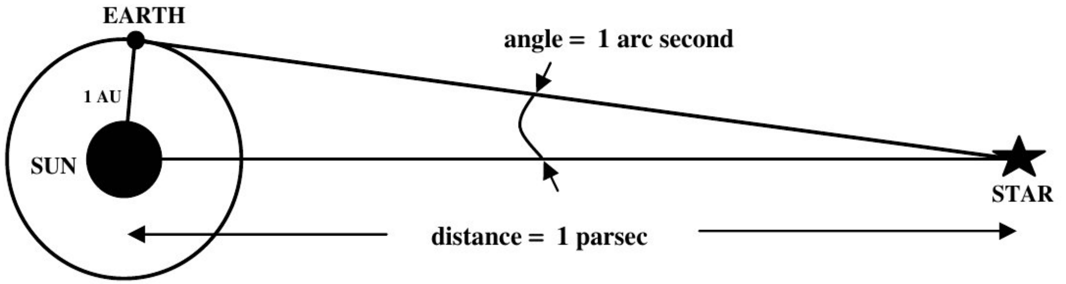
$$1\ \text{AU} = 1.496 \times 10^{11}\text{m}$$

- 1 **Light Year** (ly) is the distance travelled by light in one year.

$$1\ \text{ly} = 9.460 \times 10^{15}\text{m} = 6.323 \times 10^{4}\ \text{AU}$$

- 1 **Parsec** (pc) is defined as the distance at which the radius of Earth's orbit subtends an angle of 1″ (see Fig.1.1).

$$1\ \text{pc} = 3.262\ \text{ly} = 2.062 \times 10^{5}\text{AU} = 3.085 \times 10^{16}\text{m}$$



Schematic diagram showing the definition of 1 parsec. Note that 1° ≡ 60′ and 1′ = 60″. Thus, 1″ = 1/3600 degree

Astronomical Scales

2. Dimensions of Astronomical Objects

Unit of measurement of size

1 solar radius, $R_\Theta = 7 \times 10^8$m

3. Masses of Astronomical Objects

Mass of our galaxy ~ 10^{11} M_{sun}

Mass of globular cluster ~ 10^5 - 10^6 M_{sun}

Chandrasekhar mass limit 1.4 M_{sun}

Mass of Earth ~ 10^{-6} M_{sun}

Your mass ~ 2-5 $\times$ 10^{-29} M_{sun}

Unit of measurement of mass

1 solar mass $M_\Theta = 2 \times 10^{30}$ kg

4. Time Scales

Human race appeared about 1-7 million (10^6) years ago --- Age of Earth 4.5 billion (10^9) years --- Age of Sun is about 5 billion years --- Age of our galaxy ~ 10 billion years --- Age of Universe ~ 14 billion years.

On the other hand, if the pressure inside a star is insufficient to support it against gravity, then it may collapse in a time, which may be measured in seconds!

Astronomical Scales

- To understand the properties of astronomical objects, the smallest parts of matter, molecules, atoms and elementary particles, must be studied.

- The densities, temperatures and magnetic fields in the Universe vary within much larger limits than can be reached in laboratories on the Earth!

- The greatest natural density met on the Earth is 22,500 kg m^{-3} (osmium), while in neutron stars densities of the order of **10^{18} kg m^{-3}** are possible.

- The density in the best vacuum achieved on the Earth is only 10^{-9} kg m^{-3} , but in interstellar space the density of the gas may be **10^{-21} kg m^{-3} or even less**.

- Modern accelerators can give particles energies of the order of 10^{13} electron volts (eV). Cosmic rays coming from the sky may have energies of over **10^{20} eV**.

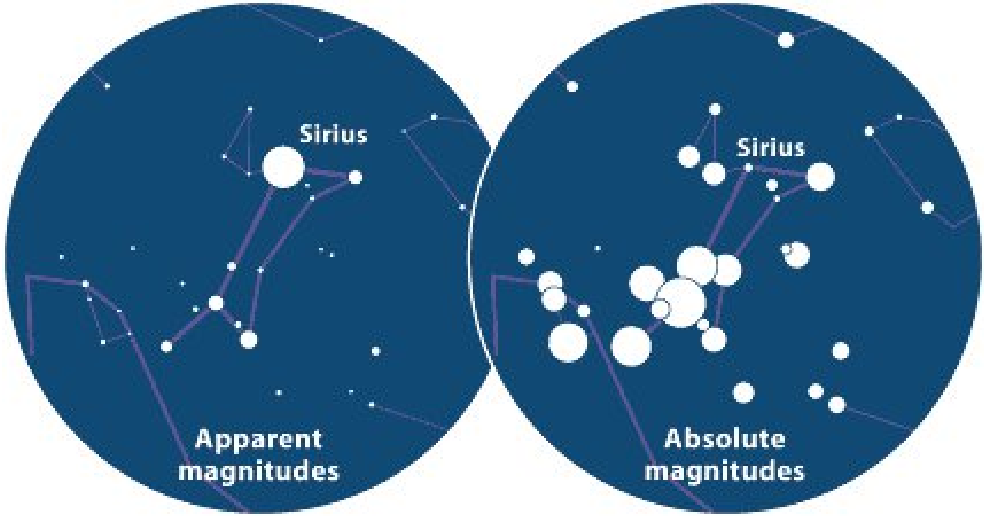
Astronomical Scales

	Distance	Radius	Mass	Remarks
Sun	1 AU	1 R_Θ	1 M_Θ	–
Earth	–	0.01 R_Θ	10^{-6} M_Θ	–
Jupiter	4 AU (5 AU from the Sun)	0.1 R_Θ	10^{-3} M_Θ	Largest planet
Proxima Centauri	1.3 pc	0.15 R_Θ	0.12 M_Θ	Nearest star
Sirius A	2.6 pc	2 R_Θ	3 M_Θ	Brightest star
Sirius B	2.6 pc	0.02 R_Θ	1 M_Θ	First star identified as white dwarf
Antares	150 pc	700 R_Θ	15 M_Θ	Super giant star

Brightness, Flux and Luminosity

- It is a common experience that if we view a street lamp from nearby, it may seem quite bright. But if we see it from afar, it appears faint. Similarly, a star might look bright because it is closer to us. And a really brighter star might appear faint because it is too far.

- We can estimate the apparent brightness of astronomical objects easily, but if we want to measure their real or intrinsic brightness, we must take their distances into account.



Brightness, Flux and Luminosity

1. Apparent Magnitude

Apparent Magnitude

Apparent magnitude **of an astronomical object is a measure of how bright it *appears*. According to the magnitude scale, *a smaller magnitude means a brighter star*.**

- In the second century B.C., the Greek astronomer **Hipparchus** was the first astronomer to catalogue stars visible to the naked eye. He divided stars into six classes, or apparent magnitudes, by their relative brightness as seen from Earth. The brightest stars are assigned the first magnitude (m = 1) and the faintest stars visible to the naked eye are assigned the sixth magnitude (m = 6).

- The magnitude scale is actually a **non-linear scale**. The response of the eye to increasing brightness is nearly logarithmic. We, therefore, need to define a **logarithmic scale for magnitudes** in which a difference of 5 magnitudes is equal to a factor of 100 in brightness.

- On this scale, the brightness ratio corresponding to 1 magnitude difference is $100^{1/5}$ or 2.512. Therefore, a star of magnitude 1 is 2.512 times brighter than a star of magnitude 2. It is $(2.512)^2$ = 6.3 times brighter than a star of magnitude 3, and so on.

Brightness, Flux and Luminosity

1. Apparent Magnitude

- Mathematically, the brightness b_1 and b_2 of two stars with corresponding magnitudes m_1 and m_2 are given by the following relations:

Relationship between brightness and apparent magnitude

$$m_1 - m_2 = 2.5\log_{10}\left(\frac{b_2}{b_1}\right)$$

$$\frac{b_2}{b_1} = 100^{(m_1-m_2)/5} \qquad \frac{b_1}{b_2} = 100^{-(m_1-m_2)/5}$$

- **The larger magnitude on negative scale indicates higher brightness while the larger positive magnitudes indicate the faintness of an object.**

Object	Indian Name	Apparent Magnitude
Sun	*Surya*	–26.81
Full Moon	*Chandra*	–12.73
Venus	*Shukra*	–4.22
Jupiter	*Guru*	–2.60
Sirius A	*Vyadha*	–1.47
Canopus	*Agastya*	–0.73
α-Centauri		–0.10
Betelgeuse	*Ardra*	+0.80
Spica	*Chitra*	+0.96
Polaris	*Dhruva*	+2.3
Uranus	*Varuna*	+5.5
Sirius B		+8.68
Pluto		+14.9
Faintest Star (detected by a modern telescope)		+29

Brightness, Flux and Luminosity

1. Apparent Magnitude

Ex. 1: Apparent magnitudes of Sun and α-Centauri are -26.81 and -0.10. Compare their brightnesses.

Solution: $m_{sun} - m_{\alpha C} = -26.81 - (-0.10) = -26.71$. Therefore,

$b_{\alpha C} / b_{sun} = 100^{-(26.71/5)} = 10^{-10.7}$

i.e. the Sun is about 10^{11} times brighter than α-Centauri.

Ex. 2. The apparent magnitude of the Sun is -26.81 and that of the star Sirius is -1.47. Which one of them is brighter and by how much?

Answer: The Sun is about 10^{10} times brighter than Sirius.

Ex. 3. The apparent magnitudes of the stars Arcturus and Aldebaran are 0.06 and 0.86, respectively. Calculate the ratio of their brightness.

Answer: 2.09

Brightness, Flux and Luminosity

2. Luminosity and Radiant Flux

The *luminosity* of a body is defined as the total energy radiated by it per unit time.

***Radiant flux* at a given point is the total amount of energy flowing through per unit time per unit area of a surface oriented normal to the direction of propagation of radiation.**

The unit of radiant flux is erg s^{-1} cm^{-2} and that of luminosity is erg s^{-1}.

In astronomy, it is common to use the cgs system of units. However, if you wish to convert to SI units, you can use appropriate conversion factors.

Note that here the radiated energy refers to not just visible light, but includes all wavelengths.

Brightness, Flux and Luminosity

2. Luminosity and Radiant Flux

Suppose a star is at a distance r from us. Let us draw an imaginary sphere of radius r round the star. The surface area of this sphere is $4\pi r^2$. Then the radiant flux F of the star, is related to its luminosity L as follows:

$$F = \frac{L}{4\pi r^2}$$

The luminosity of a stellar object is a measure of the intrinsic brightness of a star. It is expressed generally in the units of the solar luminosity, L_Θ, where

$$L_\Theta = 4\times10^{26}\,\mathrm{W} = 4\times10^{33}\,\mathrm{erg\,s^{-1}}$$

For example, the luminosity of our galaxy is about $10^{11}\,L_\Theta$.

The energy from a source received at any place, determines the brightness of the source -- this implies that *F* is related to the brightness *b* of the source; **the brighter the source, the larger would be the radiant flux at a place**. Therefore, using the previous equation, we get

$$\frac{b_2}{b_1} = 100^{(m_1-m_2)/5} \qquad \frac{F_2}{F_1} = 100^{(m_1-m_2)/5}$$

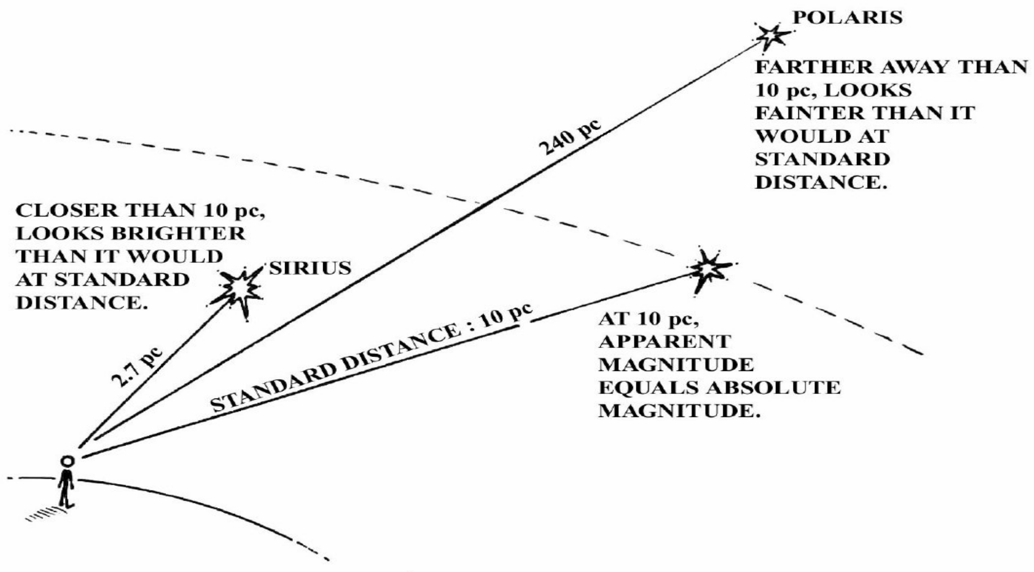
Brightness, Flux and Luminosity

3. Absolute Magnitude

- The flux received at a place depends on its distance from the source. Therefore, two stars of the same apparent magnitude may not be equally luminous, as they may be located at different distances from the observer:
- A star's apparent brightness does not tell us anything about the luminosity of the star.
- We need a measure of the **true** or **intrinsic brightness** of a star so that we could easily compare the true brightness of stars if we could line them all up at the same distance from us.

Absolute Magnitude

The *absolute magnitude*, *M*, of an astronomical object is defined as its apparent magnitude if it were at a distance of 10 pc from us.



Brightness, Flux and Luminosity

3. Absolute Magnitude

- **Relation between absolute magnitude and apparent magnitude:**

Let us consider a star at a distance *r* pc with apparent magnitude *m*, intrinsic brightness or luminosity *L* and radiant flux F_1. Now when the same star is placed at a distance of 10 pc from the place of observation, then its magnitude would be, say *M* and the corresponding radiant flux would be, say F_2. So, we have

$$\frac{F_2}{F_1} = 100^{(m-M)/5}$$

Since the luminosity is constant for the star, we can write: $\frac{F_2}{F_1} = \left(\frac{r\ \mathrm{pc}}{10\ \mathrm{pc}}\right)^2$

We can get the difference between the apparent magnitude (*m*) and absolute magnitude (*M*). **It is a measure of distance** and is called the **distance modulus.**

Distance modulus

$$m - M = 5\log_{10}\left(\frac{r\ \mathrm{pc}}{10\ \mathrm{pc}}\right) = 5\log_{10} r - 5$$

Brightness, Flux and Luminosity

3. Absolute Magnitude

- **Relation between absolute magnitude and Luminosity:**

we know that the ratio of radiant flux of two stars at the same distance from the point of observation is equal to the ratio of their luminosities. Thus, if M_1 and M_2 are the absolute magnitudes of two stars, we can relate their luminosities to M_1 and M_2.

$$\frac{L_2}{L_1} = 100^{(M_1 - M_2)/5}$$ (remember $\frac{F_2}{F_1} = 100^{(m_1 - m_2)/5}$)

or

$$M_1 - M_2 = 2.5 \log_{10}\left(\frac{L_2}{L_1}\right)$$

Thus, the **absolute magnitude of a star is a measure of its luminosity,** or **intrinsic brightness**. Whereas, the apparent magnitude is a measure of the observed flux as received by us.

Brightness, Flux and Luminosity

3. Absolute Magnitude

Ex. 1. The apparent magnitude of the Sun is – 26.8. Find its absolute magnitude. Remember that the distance between the Sun & the Earth is 1.5×10^{13} cm.

Solution: The relation between apparent magnitude m and absolute magnitude M is

$$M = m - 5 \log r + 5$$

where the distance r is in parsec. Distance of the Sun in parsec is $1.5 \times 10^{13}/3 \times 10^{18} = 5 \times 10^{-6}$. So,

$$M = -26.8 - 5\,(\log 5 - 6) + 5 = -26.8 - 5 \log 5 + 30 + 5$$

$$= 8.4 - 3.5 = 4.9$$

3. Absolute Magnitude

Ex. 2. The distance modulus of the star Vega is –0.5. At what distance is it from us?

Solution:

$$m - M = -0.5 = 5\log_{10}\left(\frac{r}{10\,\text{pc}}\right)$$

$$\log_{10}\left(\frac{r}{10\,\text{pc}}\right) = \left(-\frac{0.5}{5}\right) = -0.1$$

$$\frac{r}{10\,\text{pc}} = (10)^{-0.1}$$

$$r = 7.9\ \text{pc}$$

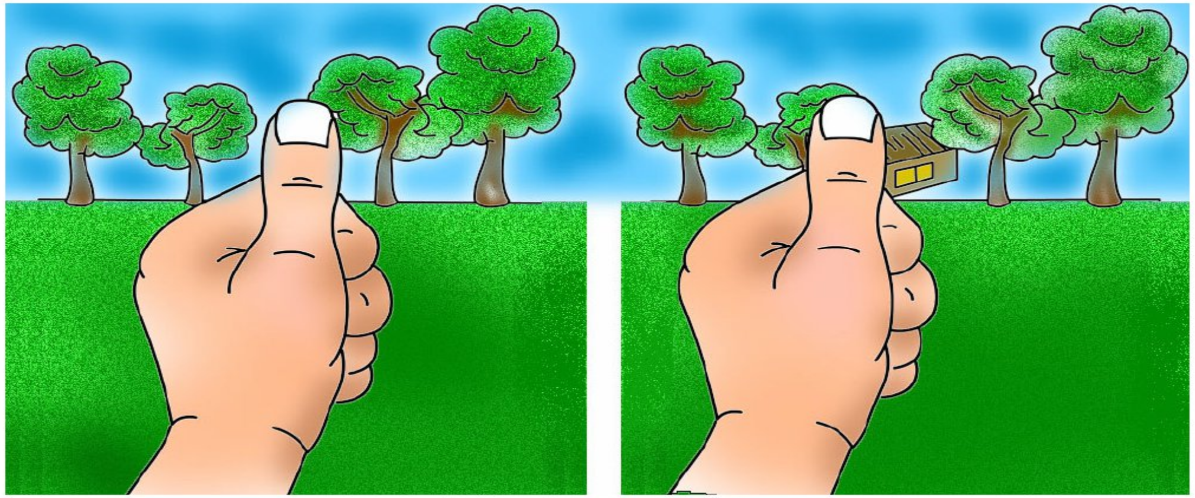
Ex. 3. If a star at 40 pc is brought closer to 10 pc, i.e., 4 times closer, how bright will it appear in terms of the magnitude?

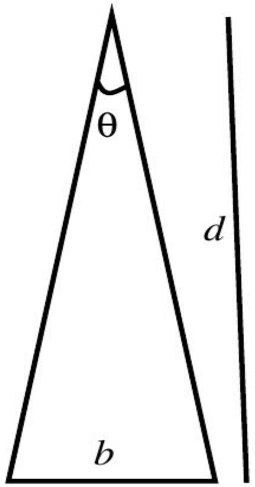
Ans: 16 times brighter

Measurement of Astronomical Quantities

1. Measuring Astronomical Distances

- Since the brightness of heavenly objects depends on their distances from us, the measurement of distance is very important in astronomy. Obviously, traditional devices like the metre stick or measuring tapes are inadequate for such measurements. Other less direct ways need to be used.
- **Parallax Method :** Parallax is the apparent change in the position of an object due to a change in the location of the observer.





We call *θ/2*, the **parallax angle**. The distance *b* between the points of observation (in this case your eyes), is called the **baseline**. From simple geometry, for small angles,

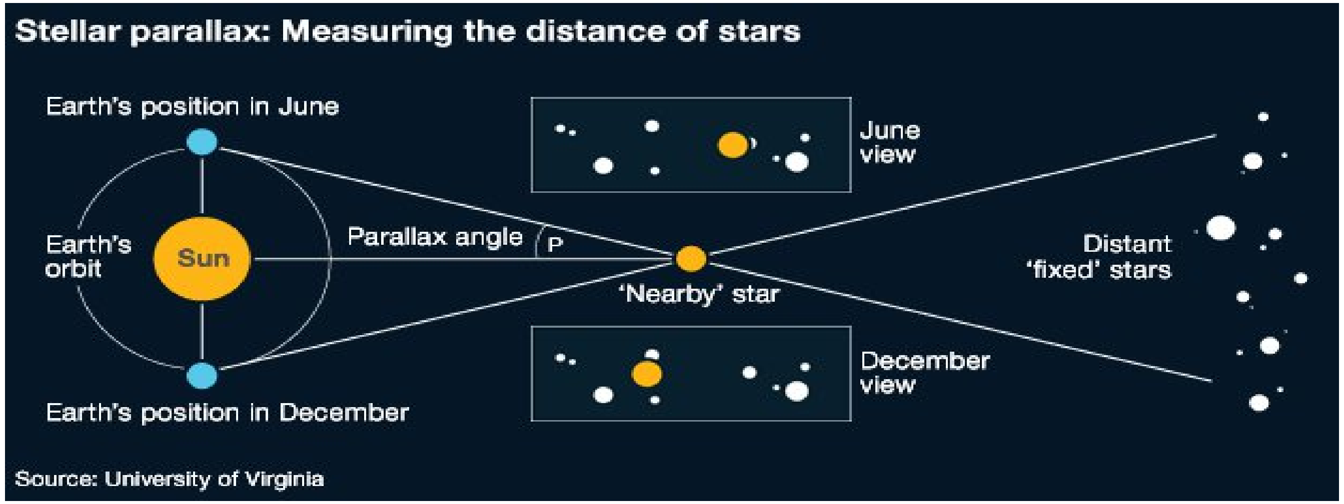
$$\frac{\theta}{2} = \frac{b}{d}$$

where *d* is the distance from the eyes to the thumb.

Measurement of Astronomical Quantities

1. Measuring Astronomical Distances

- **Stellar Parallax:**
- The motion of the Earth around the Sun produces an **apparent movement** on the sky of nearby stars, relative to more distant stars.
- Stars in the direction perpendicular to the plane of the Earth's orbit (called the **"ecliptic plane"**) will trace a circle on the sky in the course of a year (see the Fig.), whereas stars in the directions of the ecliptic plane will trace on the sky a line segment that doubles back on itself. In other directions, stars will trace out an ellipse.
- Apart from the apparent motion of stars due to parallax, stars have **real motions relative to each other**, and hence relative to the Sun. Over human timescales, these real relative motions will generally appear on the sky to have constant velocity and direction. In practice, therefore, the parallax motion of nearby stars will often be superimposed on a linear **"proper motion"** , producing a curly or wavy trajectory on the sky.



Measurement of Astronomical Quantities

1. Measuring Astronomical Distances

- **Stellar Parallax:**

For measuring the distance of a star, we must use a very long baseline. Even for measuring the distance to the nearest star, we require a baseline length greater than the Earth's diameter. This is because the distance of the star is so large that the angle measured from two diametrically opposite points on the Earth will differ by an amount which cannot be measured.

Therefore, we take the **diameter of the Earth's orbit as the baseline**, and make **two observations at an interval of six months**.

One half of the maximum change in angular position of the star is defined as its **annual parallax**. From the figure, the distance r of the star is given by

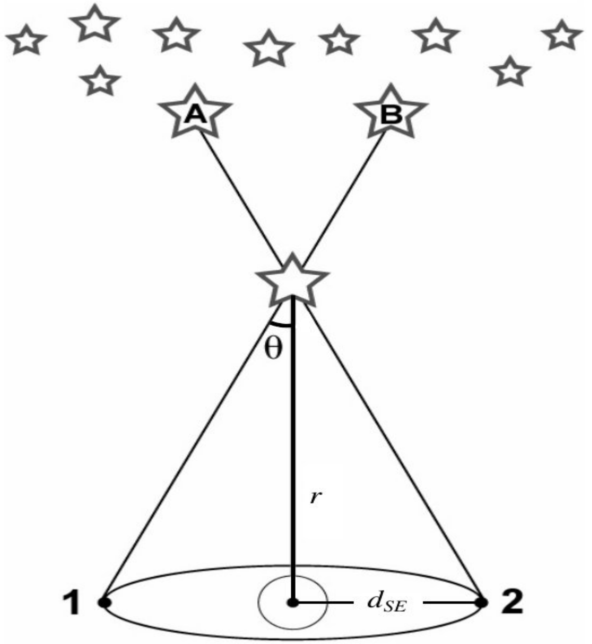
$$\frac{d_{SE}}{r} = \tan\theta$$

where d_{SE} is the average distance between the Sun and the Earth. Since the angle θ is very small, $\tan\theta \cong \theta$, and we can write

$$r = \frac{d_{SE}}{\theta}$$

Since, d_{SE} = 1 AU, we have $r = \frac{1AU}{\theta}$

Remember that this relation holds only when the parallax angle *θ* is expressed in radians.



Measurement of Astronomical Quantities

1. Measuring Astronomical Distances

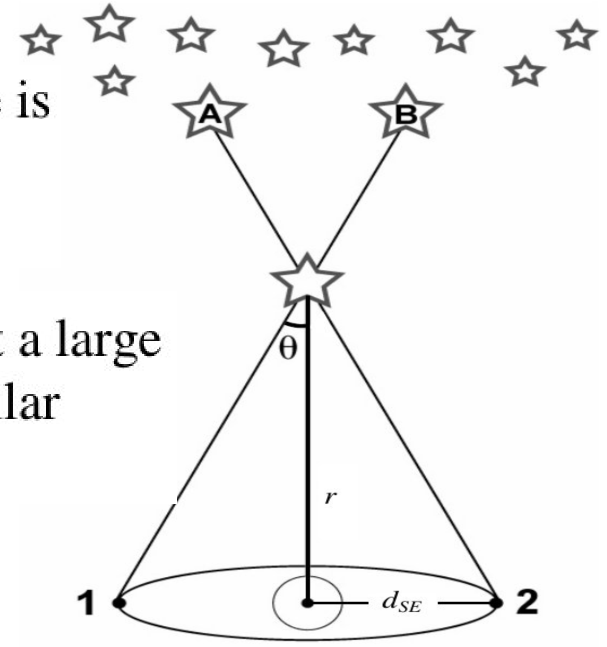
- **Stellar Parallax:**

If we measure θ in arc seconds, then the distance is said to be in parsecs.

One parsec is the distance of an object that has a *par*allax of one *sec*ond of an arc (1″).

The nearest star Proxima Centauri has a parallax angle 0.77 ″. Thus its distance is 1.3 pc. Since the distance is proportional to 1/θ, the more distant a star is, the smaller is its parallax.

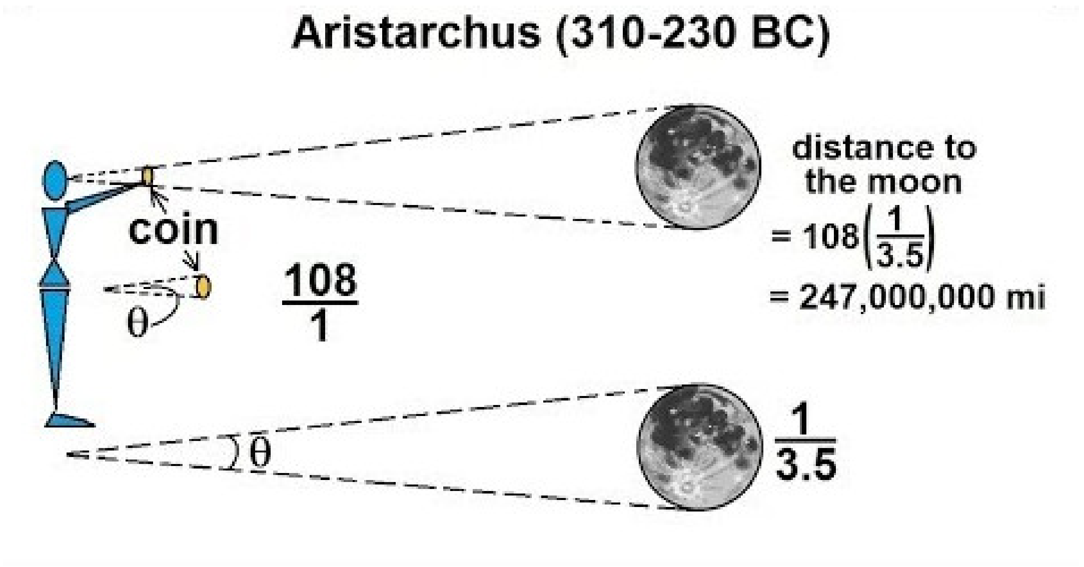
Note that the angle θ cannot be measured precisely when the stellar object is at a large distance. Therefore, alternative methods are used to determine distances of stellar objects.

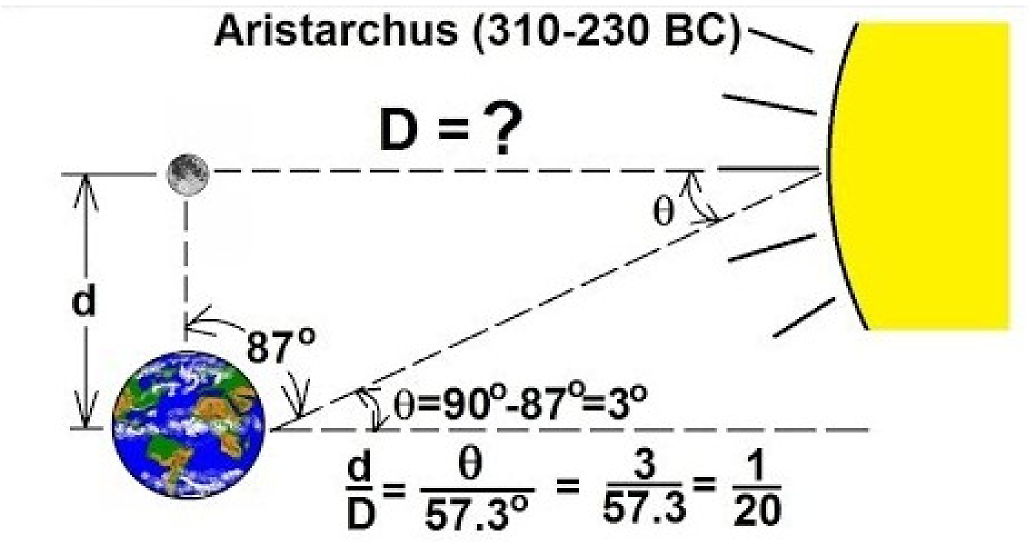


Measurement of Astronomical Quantities

1. Measuring Astronomical Distances

- **How did they determine the distance to the Moon and to the Sun?**





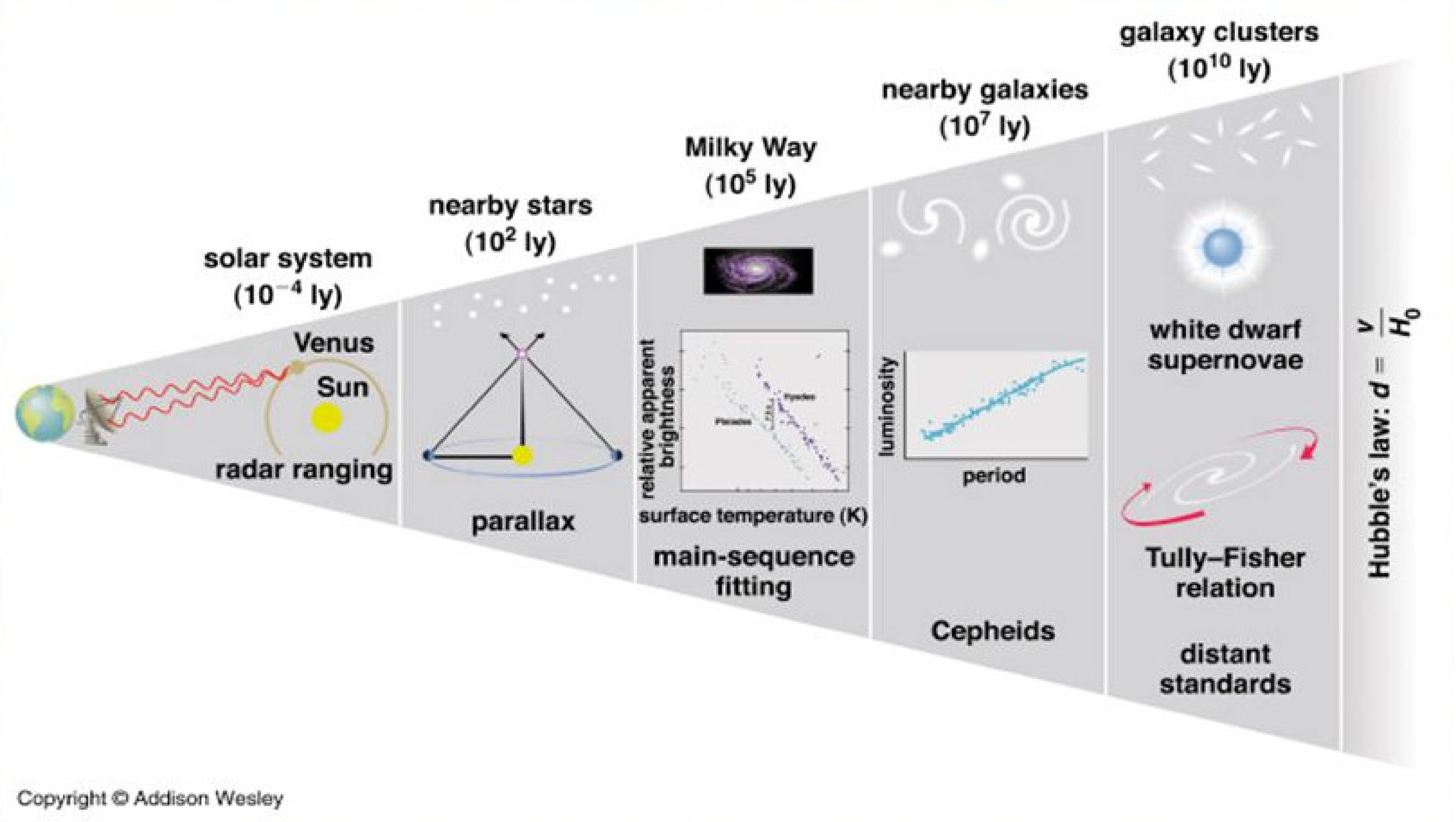
For details, visit: https://www.youtube.com/watch?v=A1puzz2Xk20

& https://www.youtube.com/watch?v=Ci88RofV7lI

Measurement of Astronomical Quantities

1. Measuring Astronomical Distances

- <u>Cosmic Distance Ladder</u>:



Measurement of Astronomical Quantities

1. Measuring Astronomical Distances

Ex. 1. a) The parallax angles of the Sun's neighbouring stars (in arc-seconds) are given below. Calculate their distances.

Star	Parallax
Alpha Centauri	0.745
Barnard's star	0.552
Altair	0.197
Alpha Draco	0.176

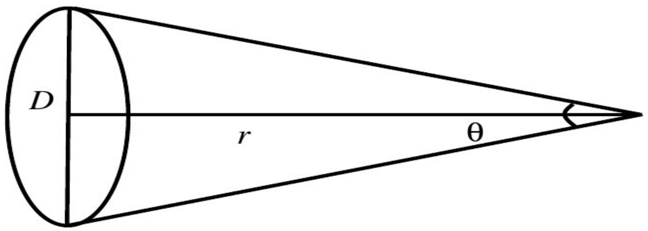
b) A satellite measures the parallax angle of a star as 0.002 arc-second. What is the distance of the star?

Answer: Use r = 1 AU / θ pc, (a) Alpha Centauri 1.34 pc, Barnard's star 1.81 pc, Altair 5.07 pc, Alpha Draco 5.68 pc. (b) Distance = 500 pc.

2. Measuring Stellar Radius

Direct Method:

We use this method to measure the radius of an object that is in the form of a disc. In this method, we measure the angular diameter and the distance of the object from the place of observation**.**



If θ (rad) is the **angular diameter** and r is the **distance of the object from the observer**, then the diameter of the stellar object will be

$$D = \theta \times r$$

This method is useful for determining the radii of the Sun, the planets and their satellites. Since stars are so far that they cannot be seen as discs even with the largest telescopes, this method cannot be used to find their radii. For this we use other methods.

2. Measuring Stellar Radius

Indirect Method:

To obtain stellar radii, we can also use **Stefan-Boltzmann law of radiation**

$$F = \sigma T^4$$

where F is the radiant flux from the surface of the object, σ, Stefan's constant and T, the surface temperature of the star. We have already known that the luminosity L of a star is defined as the total energy radiated by the star per second. Since $4\pi R^2$ (R being the radius of the star) is the surface area, we can write

$$L = 4\pi R^2 F$$

If the star's surface temperature is T, combining these two equations we get

$$L = 4\pi R^2 \sigma T^4$$

The knowledge of L and T gives R.

Measurement of Astronomical Quantities

2. Measuring Stellar Radius

Indirect Method:

Now let us consider two stars of radii R_1 and R_2 and surface temperatures T_1 and T_2, espectively. The ratio of luminosities of these two stars will be

$$\frac{L_1}{L_2} = \left(\frac{R_1}{R_2}\right)^2 \left(\frac{T_1}{T_2}\right)^4$$

Earlier, we got the relation like

$$\frac{L_2}{L_1} = 100^{(M_1 - M_2)/5}$$

where M_1 and M_2 are the absolute magnitudes. Therefore, equating these two equations, we get

$$\frac{R_2^2 T_2^4}{R_1^2 T_1^4} = 10^{0.4(M_1 - M_2)}$$

Measurement of Astronomical Quantities

2. Measuring Stellar Radius

Indirect Method:

Ex. 1. The surface temperatures of Sirius A and Sirius B are found to be equal. The absolute magnitude of Sirius B is larger than that of Sirius A by 10. Compare their radii.

Solution: $M_A - M_B = -10$ and $T_A = T_B$, So

$$R_B^2 / R_A^2 = 10^{-0.4 \times 10} \qquad \text{or,} \qquad R_B / R_A = 10^{-2}$$

Thus the radius of Sirius A is 100 times that of Sirius B.

Ex. 2. The luminosity of a star is 40 times that of the Sun and its temperature is twice as much. Determine the radius of the star.

Solution:

$$\frac{R_2^2}{R_1^2} = \frac{T_1^4}{T_2^4} \cdot \frac{L_2}{L_1} = \left(\frac{1}{2}\right)^4 \times 40$$

$$R_2^2 = \left(R_1^2\right) \times 2.5$$

$$R_2 = 1.58 R_{\Theta} \, .$$

Measurement of Astronomical Quantities

2. Measuring Stellar Radius

Indirect Method:

Ex. 3. After about 5 billion years the Sun is expected to swell to 200 times its present size. If its temperature becomes half of what it is today, find the change in its absolute magnitude.

Solution

$$\frac{(200)^2}{(2)^4} = 10^{0.4(M_1 - M_2)}$$

where M_1 is the present absolute magnitude of the Sun. Therefore,

$$M_1 - M_2 = 2.5 \log\left(\frac{200 \times 200}{16}\right)$$

$$= 2.5 \log (2500) = 2.5 \times 3.4 = 8.5$$

So, the absolute magnitude of the Sun will decrease by 8.5 and it will, therefore, become much more luminous.

Measurement of Astronomical Quantities

3. Measuring Stellar Masses

Mass is also a fundamental property of a star, like its luminosity and its radius. Unfortunately, mass of a single star cannot be found directly. If, however, two stars revolve round each other (called a **binary system**), it is possible to estimate their masses by the application of **Kepler's laws**. Fortunately, a large fraction of stars are in binary systems and therefore their masses can be determined.

Now suppose M_1 and M_2 are the masses of the two stars and a is the distance between them, then we can write **Kepler's third law** as

$$\frac{GP^2}{4\pi^2}(M_1 + M_2) = a^3$$

where P is the period of the binary system and G is the constant of gravitation. This relation gives us the **combined mass of the two stars**. However, if the motion of both the stars around the common centre of mass can be observed, then we have

$$M_1 a_1 = M_2 a_2$$

where a_1 and a_2 are distances from the centre of mass. Then both these equations allow us to estimate the **masses of both the stars**.

3. Measuring Stellar Masses

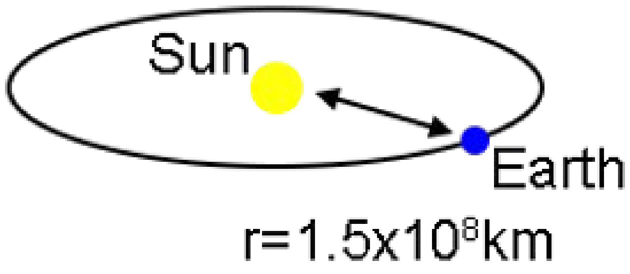
How to Measure Mass of the Sun?

As the gravitational attraction of our Sun for the Earth is equal to the centripetal force causing the Earth's circular motion around the Sun, we can use **Newton's law of universal gravitation** to find the mass of the Sun.

$$F_{gravity} = F_{centripetal}$$

$$G\frac{Mm}{r^2} = \frac{mv^2}{r}$$

$$M = \frac{v^2 r}{G}$$



- The value for G is 6.67×10^{-11} N m^2/kg^2 (where N is Newtons). The distance separating the Earth and the Sun (the orbital radius of the Earth around the Sun), r, is 1.5×10^8 km. The Earth's velocity around the Sun is just the total distance traveled divided by the time required for the Earth to make one complete orbit around the Sun, T, i.e. $v = \frac{2\pi r}{T}$.

After calculating all these, we can get mass of the Sun ~ 2×10^{30} kg.

4. Measuring Stellar Temperature

- Every star has a range of temperatures, from millions of degrees Kelvin in its core to only thousands in the outer regions.
- The emitted spectrum of a star is largely determined by the temperature in the outermost "surface", or more correctly, in its **"photosphere"**. The photosphere can be roughly defined as the region from which photons are able to escape a star without further absorption or scattering.
- By examining the emerging spectrum, one can then define various "temperatures". The **color temperature** or **thermal temperature** is the temperature of the **Planck function** with shape most closely matching the observed spectrum. For example, if we could identify the position of the peak of the spectrum, we could use **Wien's law** to set the temperature.
- Another kind of temperature can be associated with the photosphere of a star, by examining the **absorption features** at discrete wavelengths in the stellar spectrum. These absorptions are induced by atoms and molecules in the cooler, less dense, gas above the surface of last scattering. Photons with energies equal to those of individual quantum energy transitions of those atoms and molecules will be preferentially absorbed, and therefore depleted, from the light emerging from the photosphere of the star in the direction of a distant observer. The same atom or molecule, which will be excited to a higher energy level by absorbing a photon, can eventually decay radiatively and re-emit a photon of the same energy.

4. Measuring Stellar Temperature

- The wavelengths and strengths of the main absorption features, or **absorption lines** as they are often called, are primarily dependent on the level of ionization and excitation of the gas. The form of the absorption spectrum therefore reflects mainly the temperature of the photosphere, and only slightly the photosphere's chemical composition, *which is actually similar in most stars*.
- **Recall the quantum structure of the hydrogen atom:** the n th energy level of the hydrogen atom (n = 1 is the ground state) is given by the **Bohr formula**,

$$E_n = -\frac{e^4 m_e}{2\hbar^2}\frac{1}{n^2} = -13.6\,\mathrm{eV}\frac{1}{n^2},$$

where e is the electron charge in cgs units (e.s.u.), m_e is the electron mass, and $\hbar$ is Planck's constant divided by 2π.

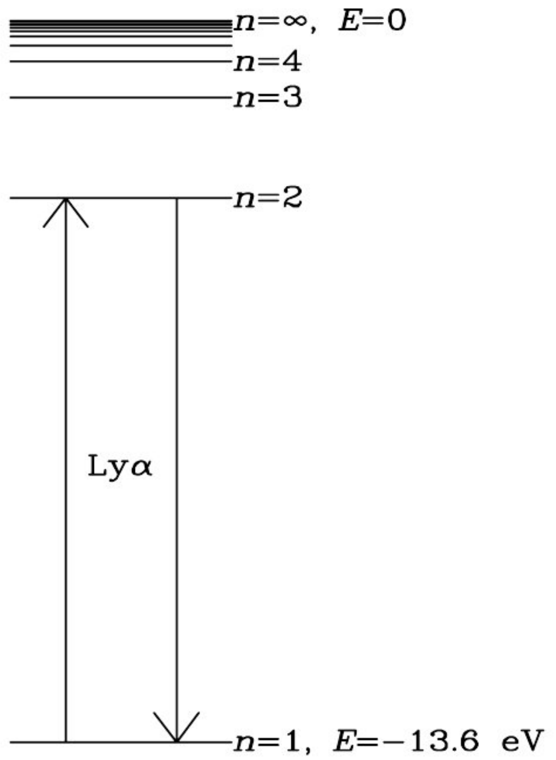
$$E_{n_1,n_2} = 13.6\,\mathrm{eV}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

The wavelength of a photon emitted or absorbed in a radiative transition between two levels will be

$$\lambda_{n_1,n_2} = \frac{hc}{E_{n_1,n_2}} = \frac{911.5\,\text{Å}}{1/n_1^2 - 1/n_2^2}$$

4. Measuring Stellar Temperature

- The **emission-line spectrum**, and is **distinct** from the **thermal (i.e., blackbody) spectrum** emitted by dense matter.



Lyα: $2 \leftrightarrow 1$, 1216 Å;
Lyβ: $3 \leftrightarrow 1$, 1025 Å;
Lyγ: $4 \leftrightarrow 1$, 972 Å;
etc.,
up until the "Lyman continuum",
Ly$_{\rm con}$: $\infty \leftrightarrow 1$, < 911.5 Å.

Lyman series
(all transitions to the n = 1 ground level)

Hα: $3 \leftrightarrow 2$, 6563 Å
Hβ: $4 \leftrightarrow 2$, 4861 Å
Hγ: $5 \leftrightarrow 2$, 4340 Å
etc.,
up until the "Balmer continuum",
Ba$_{\rm con}$: $\infty \leftrightarrow 2$, < 3646 Å.

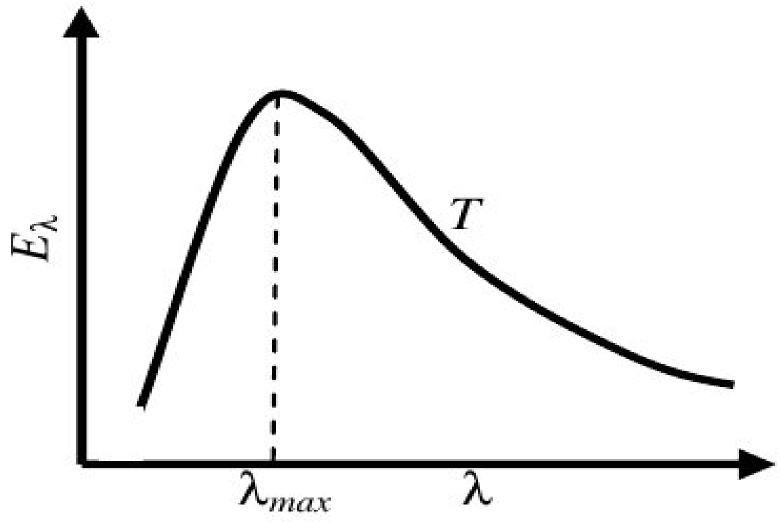
Balmer series
(all transitions to the n = 2 ground level)

Energy levels of the hydrogen atom. Arrows indicate excitation from the ground state ($n = 1$) to the first excited energy level ($n = 2$), and de-excitation back to the ground state. Such excitation and de-excitation could be caused by, e.g., absorption by the atom of a Lyman-α photon, and subsequent spontaneous emission of a Lyman-α photon.

Measurement of Astronomical Quantities

4. Measuring Stellar Temperature

- The temperature of a star can be determined by looking at its **thermal spectrum or color**. The radiant flux (F_λ) at various wavelengths (λ) is shown in this figure. This figure is quite similar to the one obtained for a **black body** at a certain temperature.
- Assuming the star to be radiating as a black body, it is possible to fit in a **Planck's curve** to the observed data at temperature *T*. This temperature determines the color of the star.



- The temperature of a star (corresponding to a black body) may be estimated using **Wien's law**

$$\lambda_{max} T_s = 0.29 \text{ cm K}$$

Such a temperature is termed as **surface temperature**, T_s.

4. Measuring Stellar Temperature

- The effective temperature of a star corresponds to the one obtained using **Stefan-Boltzman law**, i.e., $F = \sigma T_e^4$
- In general it is difficult to define the temperature of a star. For instance, the temperature obtained from line emission is indicative of temperature from a region of a star where these lines are formed. For example, the effective temperature of our Sun is around 5778 kelvins (K). Stars have a decreasing temperature gradient, going from their central core up to the atmosphere. The *"core temperature"* of the Sun, i.e. the temperature at the centre of the Sun where nuclear reactions take place, is estimated to be 15,000,000 K.
- **Relationship with Luminosity:** The luminosity L of star depends on its effective temperature T_e (measured in degrees Kelvin) and its radius R (measured in meters): $L = \sigma T_e^4 \times 4\pi R^2$, where $\sigma = 5.67 \times 10^{-8}$ W m $^{-2}$ K $^{-4}$. For example, luminosity of Sun is determined as

$$L_\odot = \left[5.67 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m^2K^4}} \cdot (5778\ \mathrm{K})^4\right] \cdot \left[4\pi \cdot \left(6.96 \times 10^8\ \mathrm{m}\right)^2\right] = 3.85 \times 10^{26}\ \mathrm{W}.$$

- When a star (of radius R and surface temperature T) is compared with the Sun, its luminosity is (as obtained previously)

$$\frac{L}{L_\odot} = \left(\frac{R}{R_\odot}\right)^2 \cdot \left(\frac{T}{T_\odot}\right)^4$$

Measurement of Astronomical Quantities

Range of Stellar Parameters

Stellar Parameters	Range
Mass	$0.1 - 100\ M_\odot$
Radius	$0.01^{*} - 1000\ R_\odot$
Luminosity	$10^{-5} - 10^{5}\ L_\odot$
Surface Temperature	$3000 - 50{,}000$ K

*It is difficult to put any lower limit on the radii of stars. As you will learn later, a neutron star has a radius of only 10 km. The radius of a black hole cannot be defined in the usual sense.

- We can find various empirical relationships among different stellar parameters, e.g., mass, radius, luminosity, effective temperatures, etc.
- Observations show that the luminosity of stars depends on their mass. We find that the **larger the mass of a star, the more luminous it is**. For most stars, the mass and luminosity are related as:

$$\frac{L}{L_\odot} = \left(\frac{M}{M_\odot}\right)^{3.5}$$

Range of Stellar Parameters

Ex. 1. The mass of star Sirius is thrice that of the Sun. Find the ratio of their luminosities and the difference in their absolute magnitudes. Taking the absolute magnitude of the Sun as 5, find the absolute magnitude of Sirius.

Solution: Using the equation $\frac{L}{L_\Theta} = \left(\frac{M}{M_\Theta}\right)^{3.5}$, we obtain $\frac{L_{\text{Sirius}}}{L_\Theta} = (3)^{3.5}$

Now using $\frac{L_2}{L_1} = 100^{(M_1 - M_2)/5}$, we get $(3)^{3.5} = 10^{0.4(M_\Theta - M_{Sirius})}$

where M_Θ and M_{Sirius} are absolute magnitudes of the Sun and Sirius.

So, $(M_\Theta - M_{\text{Sirius}}) = 2.5 \log (46.8)$

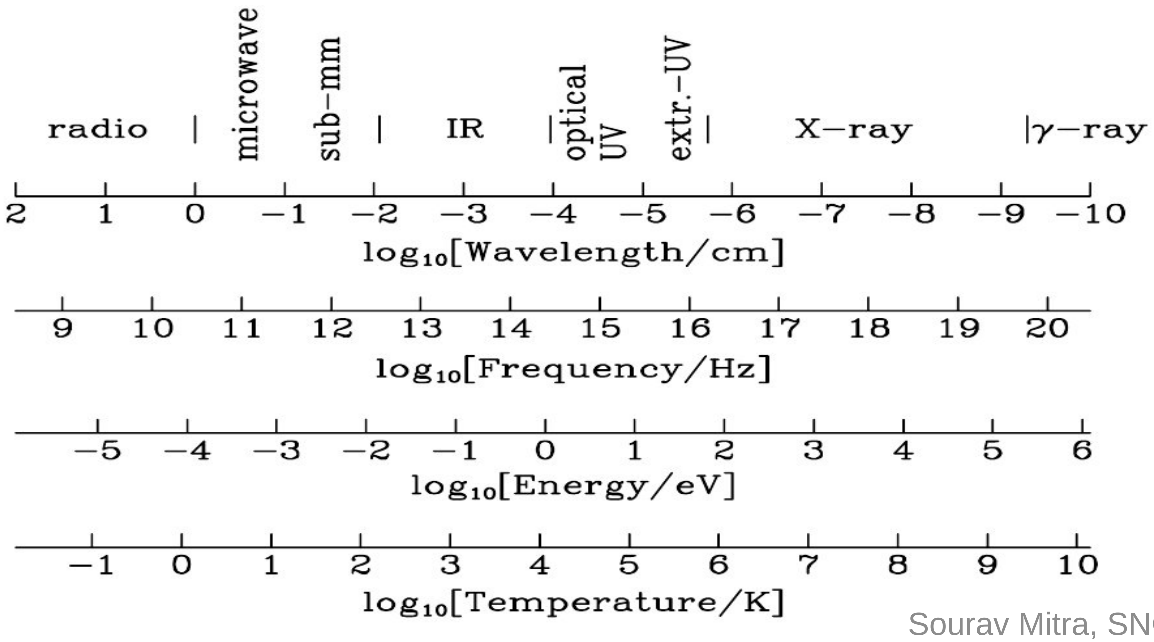
$= 2.5 \times 1.7 = 4.25.$

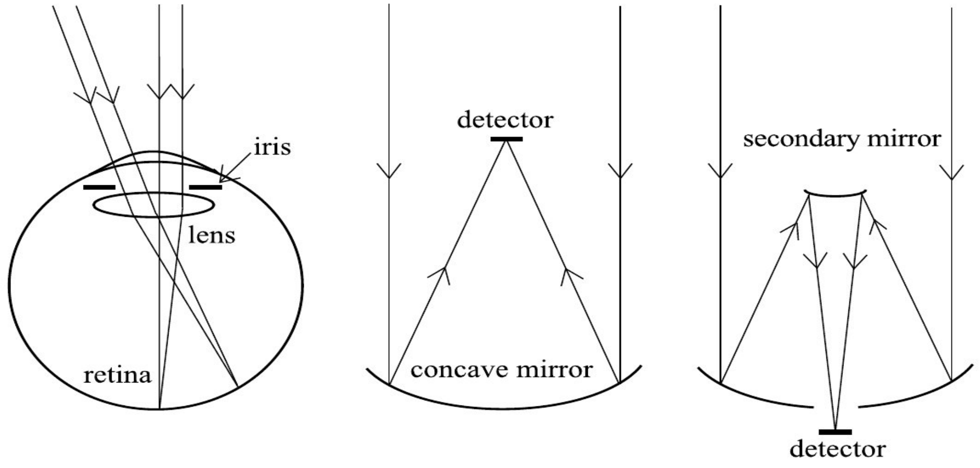
$\therefore \quad M_{\text{Sirius}} = 5 - 4.25 = 0.75.$

Observational Tools

Observational Techniques

- With several exceptions, astronomical phenomena are almost always observed by detecting and measuring **electromagnetic (EM) radiation from distant sources**. The exceptions are in the fields of cosmic ray astronomy, neutrino astronomy, and gravitational wave astronomy.
- To record and characterize EM radiation, one needs, at least, a **camera**, that will focus the approximately plane EM waves arriving from a distant source, and a **detector** at the focal plane of the camera, which will record the signal. A "telescope" is just another name for a camera that is specialized for viewing distant objects. The most basic such camera-detector combination is the human eye, which consists (among other things) of a lens (the camera) that focuses images on the retina (the detector).





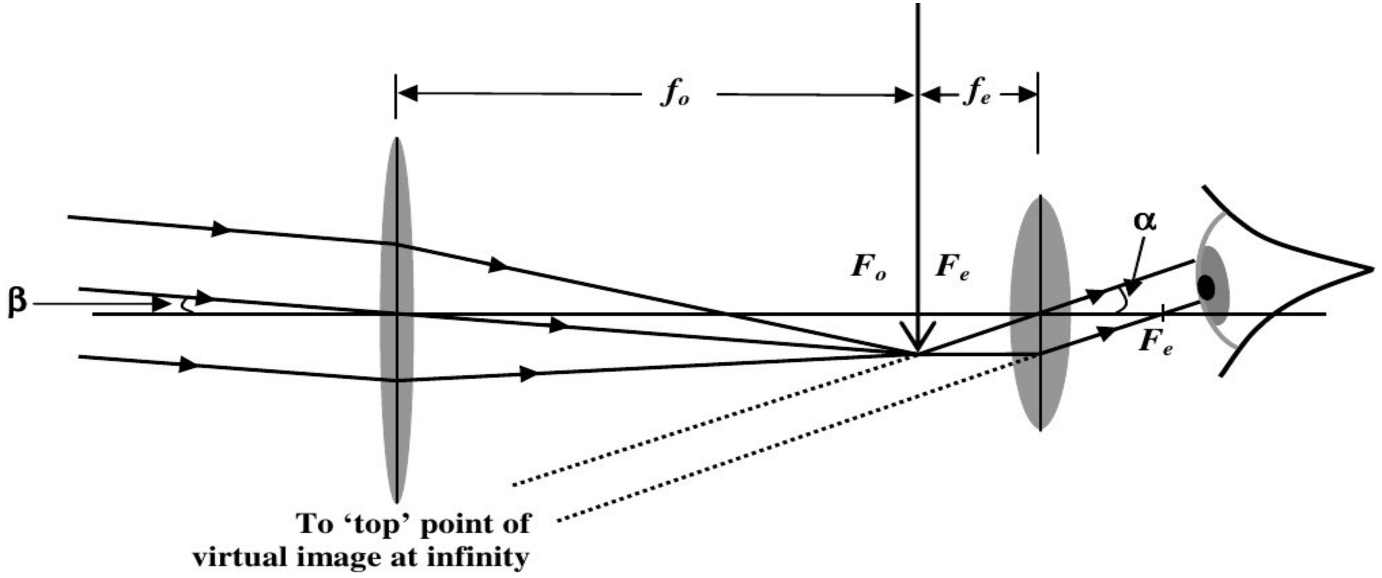
Optical sketches of three different examples of camera-detector combinations. Left: Human eye; Center: A reflecting telescope with a detector at its "prime focus"; Right: Reflecting telescope, but with a "secondary" convex mirror,

Basic Optical Definitions for Astronomy

1. Magnification:

The magnifying power of a telescope refers to its ability to make the image appear bigger. If the angle subtended by a distant object at the objective of a telescope is β and that subtended by the virtual image at the eye is α (see the Fig. below), then the **angular magnification (A.M.)** of the telescope is given by

$$\text{A.M.} = \frac{\alpha}{\beta}$$



We calculate the A.M. of a telescope by dividing the objective's focal length by the focal length of the eyepiece.

$$\text{A.M.} = \frac{f_o}{f_e}$$

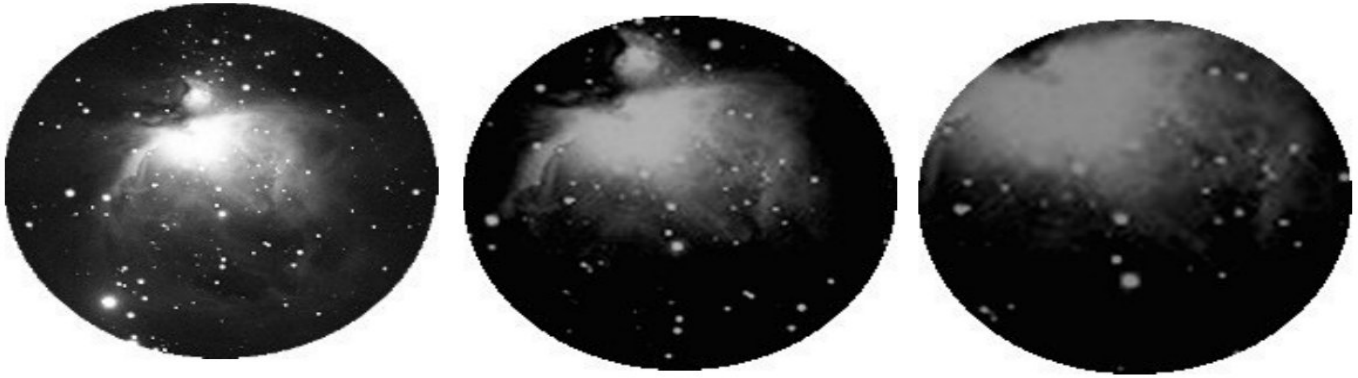
For example, if a telescope has an objective with a focal length of 60 cm and an eye-piece of focal length 0.5 cm, its angular magnification is 60/0.5, or 120 times. We say that the magnification is 120 X.

Observational Techniques

Basic Optical Definitions for Astronomy

1. Magnification:

- The highest possible magnification of a telescope is limited by its optics which includes the quality of lenses and mirrors and the thermal insulation of the telescope tube so that the exchange of heat does not disturb the air inside the tube. The magnification is also limited by the disturbance of light rays suffered in the Earth's atmosphere. Also, **the higher the magnification, the smaller is the field of view**, i.e., the area of the sky which can be observed by the telescope becomes smaller (see the Fig. below).



(a) (b) (c)

Note that, the images in Figs. (b) and (c) are dimmer compared with the one in Fig. (a). Is there a way to make it brighter? We can do so by gathering more light from the object. This brings us to the concept of light gathering power of a telescope.

Basic Optical Definitions for Astronomy

2. Light Gathering Power:

The light gathering power of a telescope refers to its **ability to collect light from an object**. Most interesting celestial objects are faint sources of light and in order to get an image we need to capture as much light as possible from them. This is somewhat similar to catching rainwater in a bucket, *the bigger the bucket, the more rainwater it catches*.

The light gathering power of a telescope is proportional to the area (i.e., diameter squared) of the telescope objective. Now, the area of a circular lens or mirror of diameter *D* is $\pi (D/2)^2$. Thus, the ratio of light gathering powers of two telescopes is given by

$$\frac{LGP_1}{LGP_2} = \left(\frac{D_1}{D_2}\right)^2$$

For example, a telescope of 100mm diameter can gather $(100/8)^2$ = 156.25 times more light than a human eye with a typical pupil diameter of 8 mm. Similarly, if we compare telescopes of 24 cm and 4 cm diameters, the former gathers $(24/4)^2$ = 36 times more light than the latter. Thus, even a small increase in telescopes diameter produces a large increase in its light gathering power and allows astronomers to study much fainter objects.

Basic Optical Definitions for Astronomy

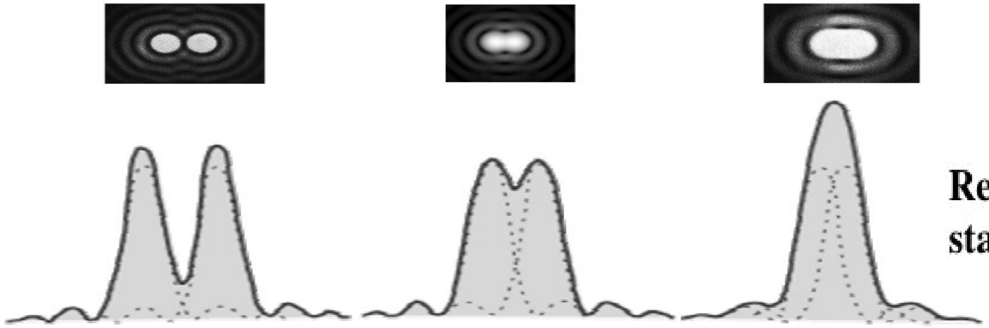
3. Resolving Power and Diffraction Limit

The ability of a telescope to reveal fine detail of an object is determined by its **resolving power.**

Suppose we wish to observe two close stars that appear equally bright. We should be able to see two **Airy discs**. However, whether we see them as distinct discs or overlapping each other, depends on the resolving power of the telescope. The two stars are said to be ***just resolved*** when we can just infer their images as two distinct Airy discs (see the Fig. below). To resolve these Airy discs, we use the **Rayleigh criterion**.

Rayleigh criterion

Two equally bright stars are said to be resolved when the central maximum of one diffraction pattern coincides with the first minimum of the other.



(a) (b) (c)

Resolving a pair of two equally bright stars. In a) the stars are easily resolved; in b) the stars are JUST resolved, and in c) the stars are too close and not resolved.

Observational Techniques

Basic Optical Definitions for Astronomy

3. Resolving Power and Diffraction Limit

A point light source observed through a telescope would not appear as a point source. **Diffraction** would cause the image to appear as a round disk of light, called **Airy's disk**. One may like to ask: What factors determine a telescope's resolving power? Naturally, the quality of lenses is a major factor. But even with perfect optics, the resolving power of a telescope is limited by diffraction.

- The **diffraction limit of resolution (*R*)** of a telescope is defined as

$$R \text{ (in radians)} = (1.22\,\lambda / D),$$

where λ is the wavelength of light and D is the telescope diameter. Both λ and D have to be expressed in the same units. R can be expressed in arc-seconds as [Note that 1 degree = 60 arc-minutes (60′) = 3600 arc-seconds (3600″)]

$$R \text{ (arc-sec)} = \frac{1.22\lambda}{D}(206265)$$

For example, in case of human eye, R ~ 1′ for absolute sharp vision, R ~ 2′ for clear vision and R ~ 4′ for comfortable vision.

- Remember that, **the smaller the value of R, the better is the instrument's ability to resolve nearby objects**.

Basic Optical Definitions for Astronomy

3. Resolving Power and Diffraction Limit

- Based on size alone, the largest telescopes should have large resolving powers. But the resolution of large telescopes is limited by the passage of light through the Earth's atmosphere. When we look through a telescope, we are looking through several kilometres of turbulent air, which blurs the image. The Earth's atmosphere does not allow ground-based telescopes to resolve better than 1-2 arc-seconds in the sky (for even the best astronomical sites).
- The major limitation for ground-based astronomy is the Earth's atmosphere and it can affect the observations in many ways. Moreover, all wavelengths cannot pass through the atmosphere. This brings us to the concept of **atmospheric windows**.

Telescope Diameter (mm)	*R* (″)
50	2.3
100	1.15
200	0.58
400	0.29
500	0.23

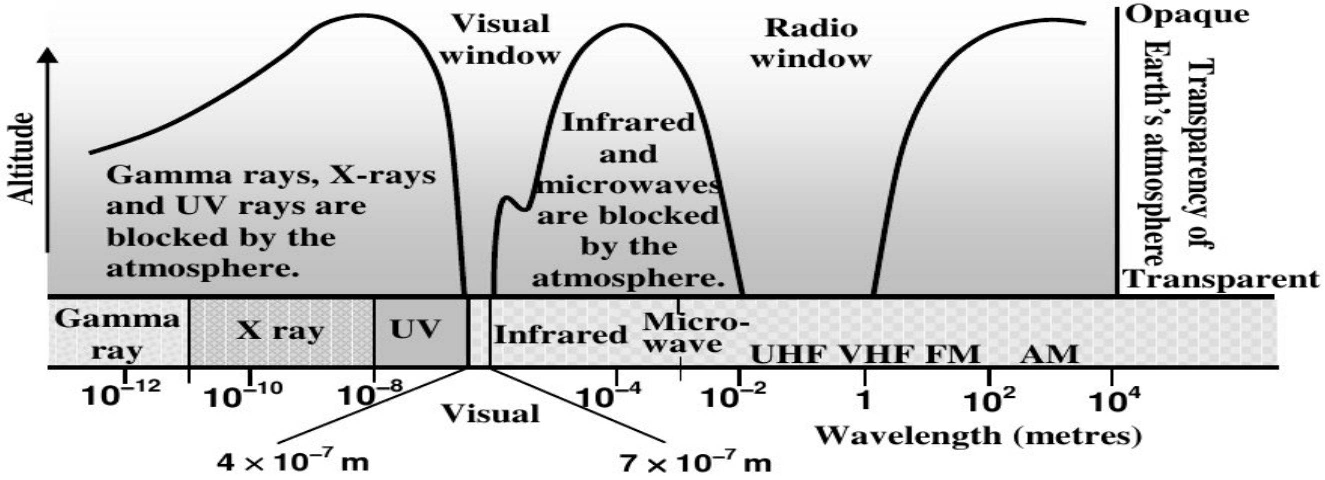
Diffraction limit of resolution of various telescopes for λ = 457 nm

Observational Techniques

Basic Optical Definitions for Astronomy

4. Atmospheric Windows

Some of the effects of the Earth's atmosphere on electromagnetic radiation are: Absorption, scintillation, scattering and turbulence. Atmospheric molecules such as carbon dioxide and water vapour give rise to absorption. Thus, only certain bands of frequencies in the electromagnetic spectrum pass through the atmosphere. These regions of the electromagnetic spectrum are called **atmospheric windows**.



The atmosphere allows **only visible radiation and radio waves to come through to the surface of the Earth**. For observations at other wavelengths we have to fly detecting instruments (balloons, rockets, space satellites etc.) to altitudes at which these wavelengths are not completely absorbed.

Observational Techniques

Basic Optical Definitions for Astronomy

- **Ex. 1:** Calculate the diffraction limit of resolution of Mount Palomar telescope of 200 inch diameter for λ = 457 nm. Compare its light gathering power with a telescope of 200 mm diameter.

Solution:

$$R = \frac{1.22\lambda}{D} \times 206265 \quad \text{arc - sec}$$

$$= \frac{1.22.457 \times 2.06265}{2 \times 2.54} \times 10^{-2} \quad \text{arc - sec}$$

$$= .023 \text{ arc - sec}$$

$$\frac{\text{LGP}_{\text{MP}}}{\text{LGP}_{\text{200mm}}} = \left(\frac{200 \times 2.54 \times 10}{200}\right)^2 = (2.54)^2 \times 10^2 = 645.2$$

Basic Optical Definitions for Astronomy

- **Ex. 2:** For the same diameter, compare the resolving power of an optical telescope operating at λ = 457 nm and a radio telescope operating at λ = 1 cm.

Solution:

$$\text{Ratio of resolving powers } = \frac{1.22\lambda_1}{D} \times 206265 \times \frac{D}{1.22\lambda_2} \times \frac{1}{206265}$$

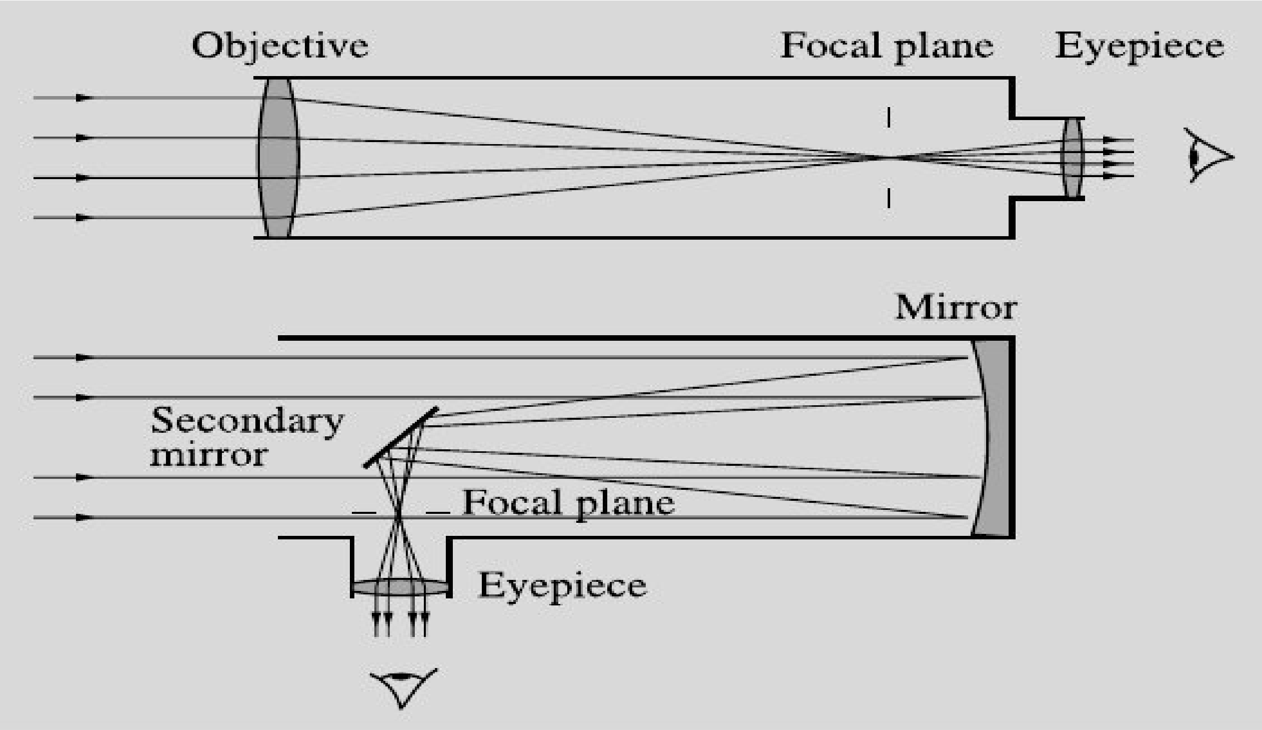
$$= \frac{\lambda_1}{\lambda_2} = \frac{4.57 \times 10^{-9} \times 10^{2}}{1}$$

$$= 4.57 \times 10^{-7}$$

Optical Telescopes

Type of Telescopes

The light-collecting surface in a telescope is either a lens or a mirror. Thus, optical telescopes are divided into two types, *lens* telescopes or **refractors** and *mirror* telescopes or **reflectors**.



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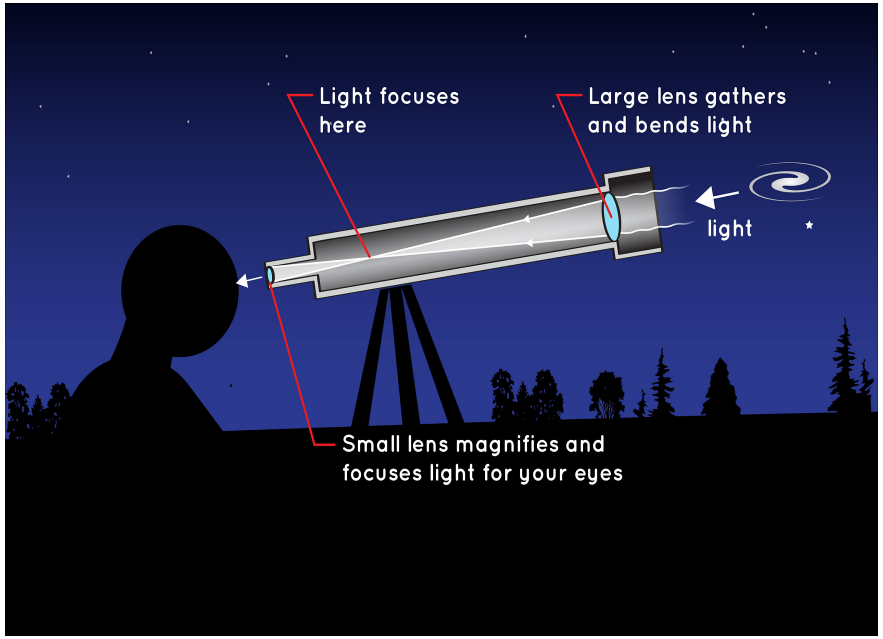


Refractors:

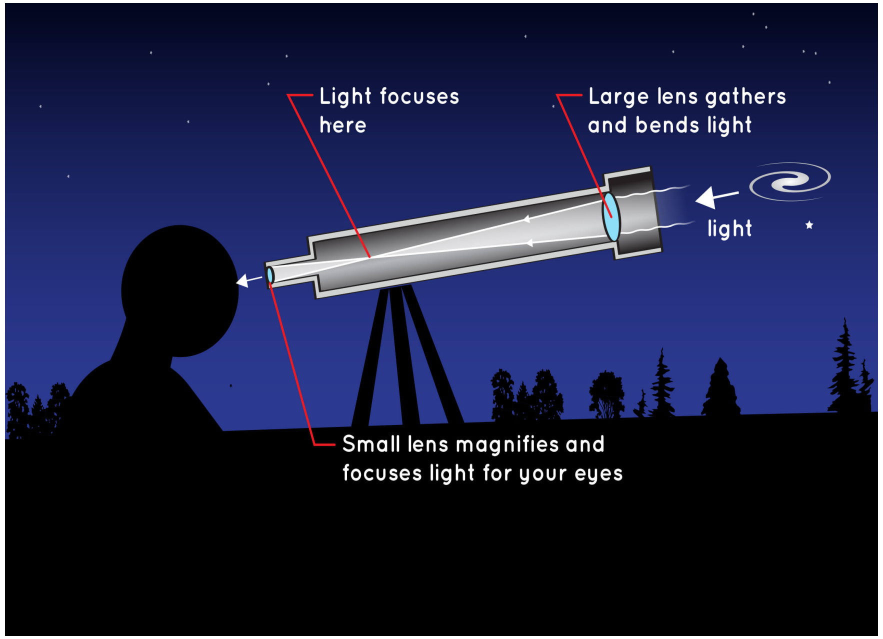
Refractors have two lenses, the **objective** which collects the incoming light and forms an image in the focal plane, and the **eyepiece** which is a small magnifying glass for looking at the image. The lenses are at the opposite ends of a tube which can be directed towards any desired point. The distance between the eyepiece and the focal plane can be adjusted to get the image into focus. The image formed by the objective lens can also be registered, e.g. on a photographic film, as in an ordinary camera.

The diameter of the objective, D, is called the aperture of the telescope. The ratio of the aperture D to the focal length f , $F = D/f$, is called the aperture ratio. This quantity is used to characterize the **light-gathering power** of the telescope.

Optical Telescopes

Type of Telescopes

The light-collecting surface in a telescope is either a lens or a mirror. Thus, optical telescopes are divided into two types, *lens* telescopes or **refractors** and *mirror* telescopes or **reflectors**.



Refractors --- Disadvantages:

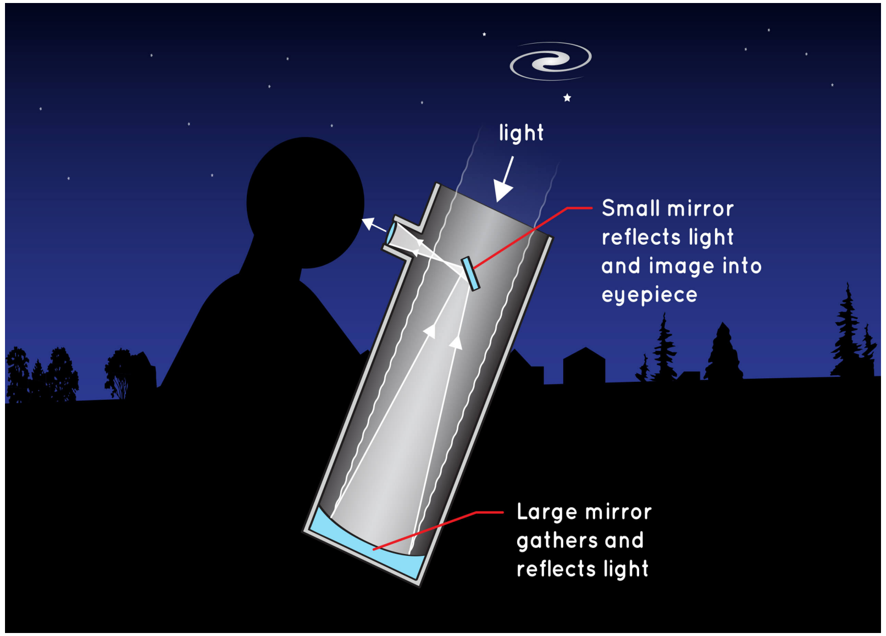
1) It is difficult to make good large lenses required for large gathering area. Also the large lenses are very heavy and balancing the telescope became difficult.
2) All refractors suffer from an effect called **chromatic aberration** ("color deviation or distortion") that produces a *rainbow* of colors around the image. Because of the wave nature of light, the longer wavelength light (redder colors) is bent less than the shorter wavelength light (bluer colors) as it passes through the lens.
3) How well the light passes through the lens varies with the wavelength of the light. Ultraviolet light does not pass through the lens at all.

Observational Techniques

Optical Telescopes

<u>Type of Telescopes</u>

The light-collecting surface in a telescope is either a lens or a mirror. Thus, optical telescopes are divided into two types, *lens* telescopes or **refractors** and *mirror* telescopes or **reflectors**.



Reflectors:

The reflector telescope uses a mirror to gather and focus light. All celestial objects (including those in our solar system) are so far away that all of the light rays coming from them reach the Earth as parallel rays. All modern research telescopes and large amateur ones are of the reflector type because of its **advantages** over the refractors telescope:

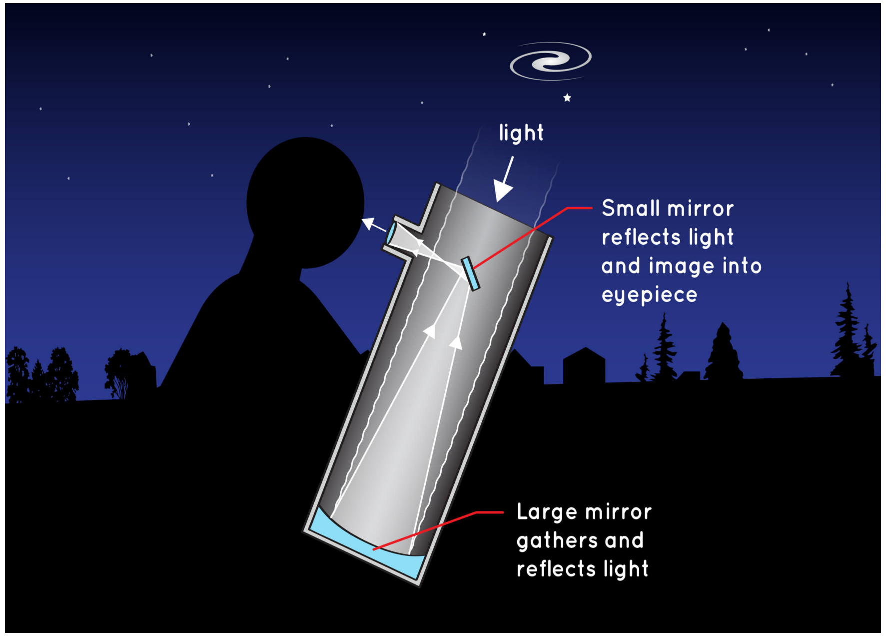
- They do not suffer from chromatic aberration because all wavelengths will reflect off the mirror in the same way.
- Support for the objective mirror is all along the back side so they can be made very BIG!
- Because light is reflecting off the objective, rather than passing through it, only one side of the reflector telescope's objective needs to be perfect.
- Reflector telescopes are cheaper to make than refractors of the same size.

Observational Techniques

Optical Telescopes

Type of Telescopes

The light-collecting surface in a telescope is either a lens or a mirror. Thus, optical telescopes are divided into two types, *lens* telescopes or **refractors** and *mirror* telescopes or **reflectors**.



Reflectors --- Disadvantages:

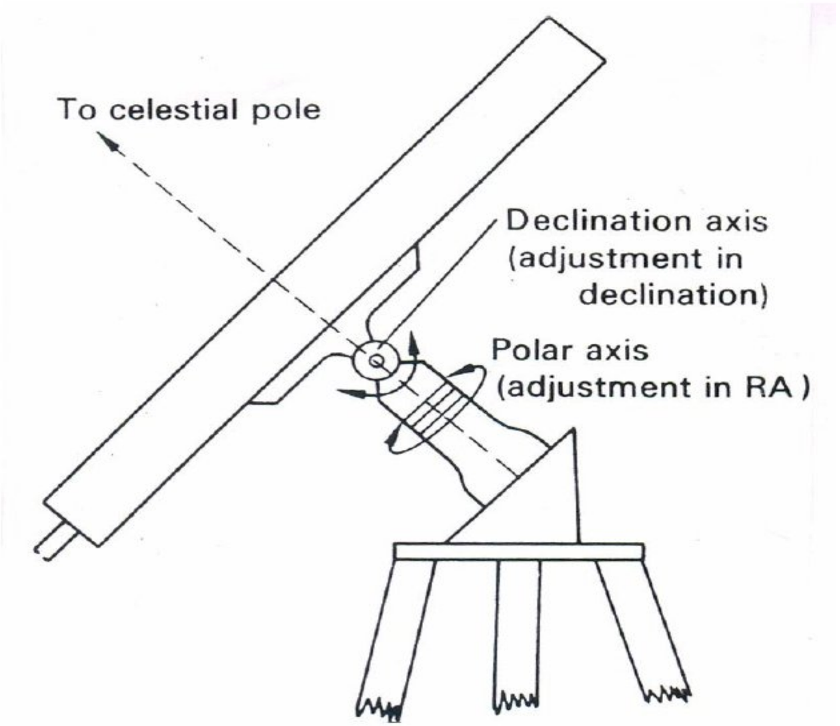
1) It is easy to get the optics out of alignment.
2) A reflector telescope's tube is open to the outside and the optics need frequent cleaning.
3) Often a secondary mirror is used to redirect the light into a more convenient viewing spot. The secondary mirror and its supports can produce diffraction effects: bright objects have spikes (the "*Christmas star effect*").

Types of Reflectors: *Gregorian, Newtonian, Cassegrain, Schmidt* telescopes.

Optical Telescopes

Telescope Mountings

A telescope has to be mounted on a steady support to prevent its shaking, and it must be smoothly rotated during observations. There are two principal types of mounting: **equatorial** and **azimuthal**.



Equatorial mount:

Most of the small telescopes (less than 1 metre diameter) use the **equatorial mount**.

- In this mounting, the pier or the base on which the telescope is mounted is set so that its **axis points to the North Pole**. This is done by raising the axis by an angle equal to the latitude of the place. This axis is called the **polar axis**.
- A rotation about the polar axis is used for adjustment in **right ascension (RA)**. The telescope is also provided with motion about an axis perpendicular to the polar axis, called the **declination** axis, for adjustment in declination. Thus, a combination of these two motions allows the telescope to point to any object whose equatorial coordinates are known.

Observational Techniques

Optical Telescopes

Telescope Mountings

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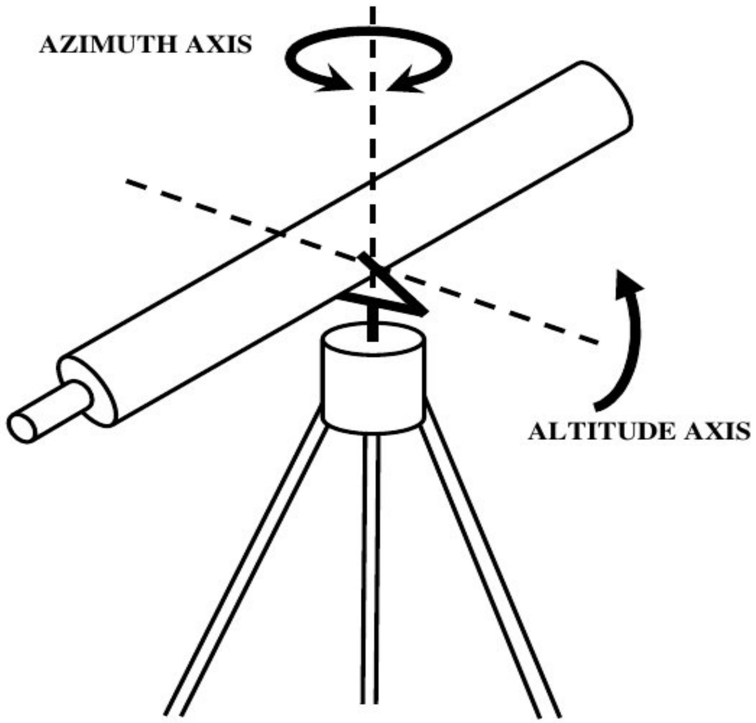


Alt-Azimuth type mount:

Since the telescope is fixed on the Earth, it moves with the Earth. In order that the object remains in the field of the telescope, the mounting is made to rotate in the direction opposite to that of the Earth with the same speed as that of the Earth. All these adjustments are easily possible in **altitude-azimuth mounting.** All modern telescopes (larger that 2 m diameter) use Alt-Azimuth type mount.

- In this mounting, one of the axes is vertical, the other one horizontal. This mounting is easier to construct than the equatorial mounting and is more stable for *very large telescopes*.
- In order to follow the rotation of the sky, the telescope must be turned around both of the axes with changing velocities. The field of view will also rotate; this rotation must be compensated for when the telescope is used for photography.

Observational Techniques

Radio Telescopes

A radio telescope has a specialized **antenna** and **radio receiver** used to receive radio waves from astronomical radio sources in the sky. Such telescopes have typically large parabolic ("**dish**") antennas similar to those employed in tracking and communicating with satellites and space probes. They may be used singly or linked together electronically in an array.

- Since astronomical radio sources such as planets, stars, nebulas and galaxies are very far away, the radio waves coming from them are *extremely weak*, so radio telescopes require *very large antennas* to collect enough radio energy to study them, and extremely sensitive receiving equipment.
- Radio observatories are preferentially located far from major centers of population to avoid electromagnetic interference (EMI) from radio, television, radar, motor vehicles, and other man-made electronic devices.

Giant Metrewave Radio Telescope (GMRT)
Pune, India

The main difference between a radio telescope and an optical telescope is in the recording of the signal. Radio telescopes are not imaging telescopes (except for some); instead it just transfers the signal to a receiver. The wavelength and phase information is, however, preserved. Also, unlike optical telescopes, radio telescopes can be used in the daytime as well as at night. The resolving power of a radio telescope, θ, can be deduced from the same formula as for optical telescopes, i.e. $\boldsymbol{\theta = 1.22 \times \lambda/D}$,

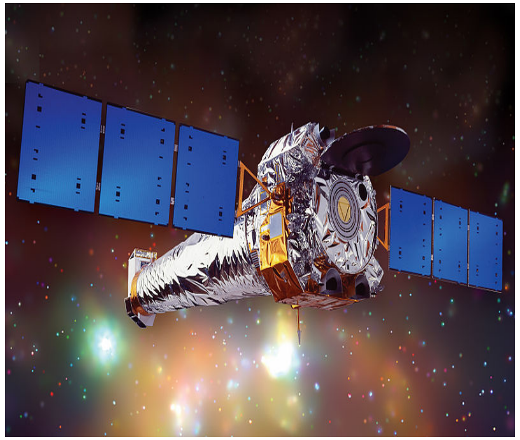
where λ is the wavelength used and D is the diameter of the aperture.

Some examples: Very Large Array (VLA) (USA), Atacama Large Millimeter Array (ALMA) (Chile), GMRT (India), Square Kilometer Array (SKA)

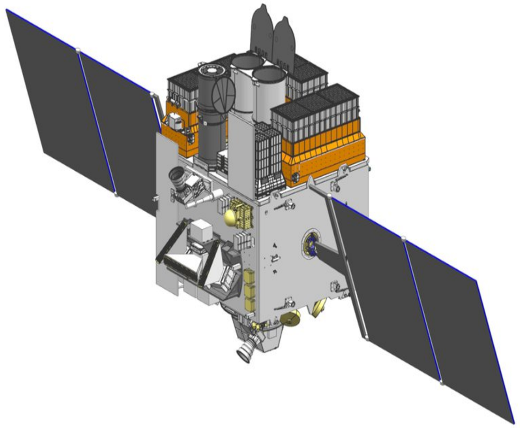
Space Telescopes

For light collection, one could fabricate telescopes of increasingly large diameters. But these will be limited by the effect of the Earth's atmosphere. However, if we could put a **telescope in space** (high above the Earth's atmosphere, in a balloon or a satellite), then the Earth's atmosphere would not be a limiting factor, and we could achieve diffraction-limited images. In such situations the size of the telescopes that can be built for such platforms is the only limitation due to the costs involved and limitations of available technology.

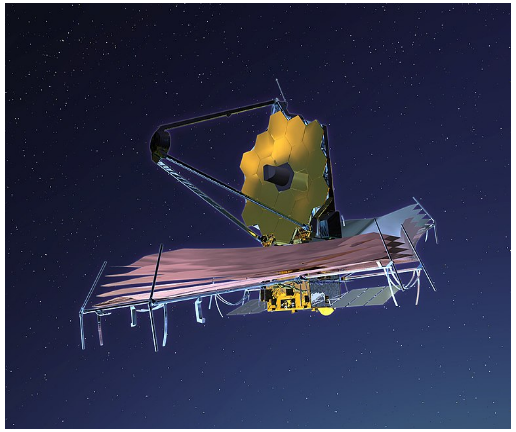
Hubble Space Telescope
NASA & ESA



Chandra X-ray Observatory
NASA



Astrosat
ISRO



James Webb Space Telescope (JWST)
NASA/ESA/CSA
(Future Gen.)

Observational Techniques

Detectors and Instruments

Only a limited amount of information can be obtained by looking through a telescope with the unaided eye. Yet until the end of the 19th century this was the only way to make observations.

- The invention of photography in the middle of the 19th century brought a revolution in astronomy. The next important step forward in optical astronomy was the development of photoelectric photometry in the 1940's and 1950's. A new revolution, comparable to that caused by the invention of photography, took place in the middle of the 1970's with the introduction of different semiconductor detectors.

The sensitivity of detectors has grown so much that today, a 60 cm telescope can be used for observations similar to those made with the Palomar 5 m telescope when it was set in operation in the 1940's.

- Detectors are used with telescopes in the following two modes of operation:

1) **Imaging:** This involves taking direct pictures of star fields and extended objects like gas clouds or galaxies. Since sharp images are required over a wide field which may extend up to several square degrees, careful optical design is a natural requirement.

2) **Photometry:** This involves measuring total brightness, spectrum etc. of single objects. Compared to imaging mode, poorer images are acceptable in this case but the stellar image has still to be small enough to enter an aperture or slit of a spectrograph.

Examples: The human eye, photographic emulsion, photometer and **charge-coupled devices (CCD)** are various types of detectors. Of these the CCDs are used most by modern astronomers. These are used for recording images, measuring brightness and color of celestial objects.