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ASTRONOMY AND ASTROPHYSICS

By: *Subhash Deo*, B.E. (Ele.), P.G.D. (OR & SQC)

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BASICS OF ASTRONOMY

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FROM STARS TO OUR GALAXY

GALAXIES AND THE UNIVERSE

❑❑

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of the
Solved
Sample Question
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QUESTION PAPER

(June – 2019)

(Solved)

ASTRONOMY AND ASTROPHYSICS

Time: 2 Hours] *[Maximum Marks : 50*

Note: *Attempt* ***all*** *questions. Symbols have their usual meanings. Use of non-programmable calculators or log tables is allowed.*

Q. 1. Attempt the following parts :

(a) **The distance modulus of the star Vega is –0. 5. At what distance is it from us?**

Ans. Ref.: See Chapter-1, Page No. 11, Q. No. 3.

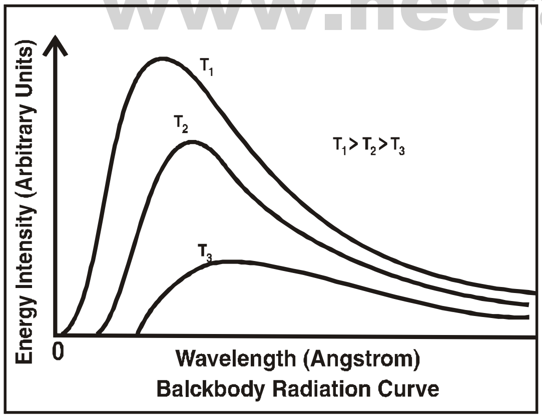
(b) **Calculate the magnitude of the faintest object that the 1.04 m telescope at ARIES, Nainital can detect.**

Ans. Telescope at Aries Nainital can detect

$$= 7.5 + 5 \log (1.04)$$
$$= 7.78.$$

(c) **Draw Balckbody radiation curves for three objects with mean temperatures T_1, T_2 and T_3 respectively, such that $T_1 > T_2 > T_3$.**

Ans.



(d) **List different layers of the Sun's atmosphere. Explain why the temperature in the chromosphere increases with height.**

Ans. Different layers of the Sun's atmosphere are :

(i) Sun interior
(ii) Photosphere
(iii) Chromosphere
(iv) Transition Zone
(v) Corona

The temperature in the chromosphere increases with height. Hot gas, in shape of jets called spicules exist upward in the chromosphere up to ~ 1000 km height and last for even 15 minutes. This means the lower part of the chromosphere is highly turbulent and the spicules transport energy and matter from the photosphere to the chromosphere. This leads to heating of the chromosphere.

(e) **With an appropriate diagram, explain the phenomenon of interstellar reddening.**

Ans. Interstellar Reddening: Yet another manifestation of interstellar dust is in the form of interstellar reddening.

An O star should be blue in colour. But, it has been observed that some stars with the spectrum of an O star look much redder. This is caused due to scattering of light from stars by interstellar dust.

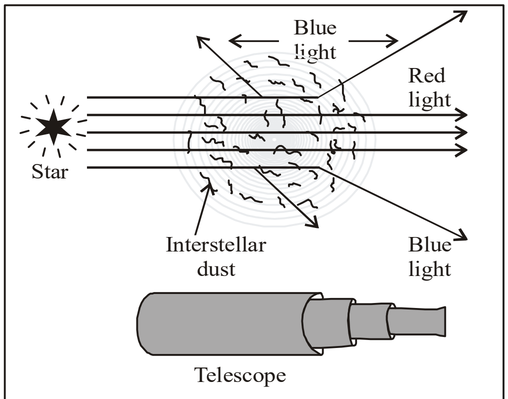


Fig. : Interstellar reddening caused by scattering of blue light coming from star

Fig., the light coming from a star behind the dust cloud is scattered. Since the typical size of dust grains is of the order of the wavelength of blue light, the blue light from the star is scattered more than the red light. As a result, some of the blue light from the star is lost and it appears redder.

***(f)* Obtain an expression for Schwarzschild radius of a star of mass M.**

Ans. Using conservation of energy to a photon emitted from a star of mass M

$$\frac{1}{2}mc^2 = \frac{GMm}{r}$$

Here, m denotes the equivalent mass of a photon.

$$\Rightarrow \qquad r = \frac{2GM}{C^2}.$$

***(g)* Distinguish between spiral and barred spiral galaxies giving one example of each type.**

Ans. A spiral galaxy has a disc, a bulge and a halo. The center of the galaxy is like a nucleus containing a sphere shaped bulge that houses old stars and is devoid of dust and gas. The circular shape of the galaxy composes the disk. The arms of the spiral galaxy originate in the disk and are where new stars will form in a galaxy. Example, the Pinwheel Galaxy Barred spiral galaxies have same features and functions as regular spiral galaxies, but they also have a bar of bright stars that lie along the center of the bulge and extend into the disk. The bright bulge has very little activity and contains mostly older, red stars. The bar and arms have lots of activity including star formation. Example, milky way galaxy, etc.

***(h)* Distinguish between an evolving and a steady-state universe. Which of the two is supported by cosmic microwave background radiation?**

Ans. Ref.: See Chapter-15, Page No. 154, 'Evolving *vs.* Steady State'.

Also Add: Evolving universe supported by cosmic microwave background radiation.

Q. 2. What do you understand by the terms resolving power and diffraction limit of an optical telescope ? Compare the resolving power of an optical telescope operating at 457 nm and a radio telescope operating at 300 MHz both having the same diameter.

Given that $c = 3 \times 10^8 \text{ms}^{-1}$.

Ans. Ref.: See Chapter-3, Page No. 27, 'Resolving Power and Diffraction Limit'.

Also Add: Wavelength of optical telescope, $\lambda_1 = 457\text{nm} = 4.57 \times 10^{-7}\text{m}$.

Wavelength of radio telescope, $\lambda_2 = \frac{c}{v} = \frac{3\times10^8}{300\times10^6} = 1\text{m}$

Ratio of resolving power

$$= \frac{1.22\,\lambda_1}{D} / \frac{1.22\,\lambda_2}{D}$$

$$= \frac{4.57\times10^{-7}}{1} = 4.57 \times 10^{-7}.$$

Or

Draw the horizon coordinate system to locate the position of a star. Suppose you wish to point a small telescope to a star whose azimuth is 30° and altitude is 60°. Describe the procedure you will adopt.

Ans. Ref.: See Chapter-2, Page No. 15, 'Horizon System'.

Also Add: Procedure to point a small telescope to a star.

Step 1: The telescope will be turned 30° degrees from North to West, keeping it horizontal.

Step 2: Then the telescope will be raised in such a way that it makes an angle of 60° with the horizontal.

Q. 3. Sunspots are the region on the Sun's surface with average temperature around – 4500 K. Why do they appear dark? What is the basis to conclude that the Sun is a rotating star about its axis? Calculate the strength of the magnetic field

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The Chapter

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ASTRONOMY AND ASTROPHYSICS

Basics of Astronomy

1

Astronomical Scales

INTRODUCTION

One of the oldest sciences in human history is Astronomy. Right from the days when man was living in the caves and then in the open, he always wondered about the things happening in the skies above. Soon mankind realized the regularity of the motions of planets, and stars, the timely rising, and setting of Sun and Moon, and found their practical utility for measuring time during days, nights and various seasons.

The recurring astronomical events helped man in clearly defining the time intervals of a day, a night, a month and a year. The changing sky in the nights around the year guided then in planning the planting of crops and harvesting them. Astronomical events also helped people in forecasting rains, summer and winter seasons, and the floods in areas where they lived. After development of commerce, business, and trade, land and sea travel became inevitable. In such long journeys the stars became invaluable navigational aids.

As mankind progressed, man became curious about the objects in the sky, and understanding their nature. Naturally he wanted to know what exactly the stars and the planets were; why they were moving in particular ways, what was their origin, what was the source of their light; and so on. To obtain answers to these questions men started observing the sky-objects, and recording and analyzing those observations. Various people put forward various hypotheses based on their own observations.

Thus study of astronomy really marked the true beginning of both science and mathematics.

Astronomy is of entirely different nature than other subjects. Many astronomical events and phenomenon have not been completely understood even today. Many of its mysteries are yet unsolved. In astronomical studies, the objects of our study cannot be touched. They cannot be brought to laboratories to perform experiments on them. Only their models can be made and experiments made with such small size models help to predict certain consequences, which can be later tested with actual observations. If the discrepancy between the two is large the model is modified and new experiments are made using it.

Sometimes sweeping assumptions are also made to make some progress in study at some aspect of astronomy. When we consider this fact, it is amazing that we still know so much in astronomy. Right now, many topics in astronomy, and in related subjects of astrophysics and cosmology have being probed further. In this and chapters that follow we study some vital topics like.

1. Estimation of distance and brightness of celestial (Space) objects.
2. Coordinate systems that help in locating these objects.
3. Daily motions of Sun, Moon and planets, and observed stars.
4. The evolution of stars.
5. Formation of elements in the universe.
6. Structures of Milky Way (Aakash Ganga in Indian Khagolshastra) and other observed galaxies,
7. Structure of the universe and its origin.

CHAPTER AT A GLANCE

In this chapter, we focus on how to estimate brightness and distances of objects in the space. Knowing these things can help us in understanding their nature. Also important is correctly determining their location so that repeated observations about them can be made.

We learn the method of Parallax to estimate the distances of stars and other objects. This method uses the common triangulation method of trigonometry. However, it is good for nearby objects only. Error in measurement becomes much larger as distance becomes large. Parallax method remains useful as the basis of some advanced methods for finding the larger distance.

We also learn about various astronomical quantities commonly used. Among these is the apparent brightness of an object. This is expressed in apparent magnitude that is a logarithmic scale. After the apparent magnitude and distance of any object, are known, its absolute magnitude can be easily decided. Absolute magnitude is the measure of true brightness, or luminosity, of an object.

Our universe is so vast that it seems to be endless in every direction. The sun is one of the billions of stars located in one of the billions of gallaxies. The distances between stars and planets are extremely large. Their masses are also huge. As an example, the distance between the Earth and the Sun is as large as 1.5×10^{30} m. The radius of the Sun is about 7×10^{8} m, which is almost 100 times the radius of the Earth, Earth's mass is about 10^{24} kg and the Sun's mass is one million times of Earth's mass.

The time scales involved are also huge. Thus, Sun is estimated to be about 5 billion years old. The universe to be more than 13 billion years in age, and the earth as young as 1.3 billion years. Compared to this a human being lives mostly for less than just 100 years.

These numbers are so big that special methods are needed to measure them and represent them.

Distance is important because a star may appear bright because it is closer or the distance might be more and the brightness might be its intrinsic quality. Also, the mass of a star tells us how it will evolve.

Here, we study physical quantities in astronomy including distance, size, mass, time, brightness, radiant flux, luminosity, temperature and their measurement scales. We will also learn about how to compare the brightness and luminosity of astronomical objects. Finally we discuss the methods of determining the distance, size and mass of such objects using given data.

ASTRONOMICAL MASS, DISTANCE AND TIME SCALES

The measuring scales of physical quantities are totally different in astronomy than what we use in our daily life. This is because of their enormous values.

(*a*) **Astronomical Distance**

(*i*) The Sun is at a distance of 1.496×10^{4} m from the earth. This is the mean distance between them. It is taken as one astronomical unit (AU) of distance in astronomy. Distances in the solar system are measured in this chapter.

(*ii*) To measure distances between stars and gallaxies, the unit of light year is used. One Light Year is the distance travelled by light in one year.

1 Light Year (ly) = 9.460×10^{15} m = 6240 AU

(*iii*) The third unit of distance measurement is Parsec (pc). One Parsec (pc) is the distance at which the radius of Earth's orbit subtends an angle of 1" (Fig. 1.1)

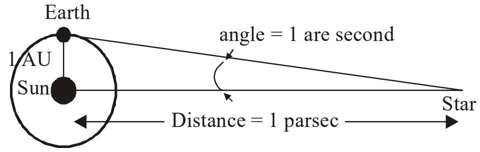

Fig. 1.1: Schematic diagram showing the definition of 1 parsec. Note that 1° = 60' and 1' = 60". Thus, 1" = 1/3600 degree

Here 1" = 1/3600 degrees. Also 1° = 60, and 1' = 60".

Hence, 1 pc = 3.262 ly = 2.060×10^{5} AU
= 3.804×10^{16} m

(*b*) **Dimensions of Astronomical Objects**

The size of stars or stellar dimensions are mostly stated in the units of solar radius $R_\ominus$. Thus, Sirus the brightest star in the sky, has a radius of $2R_\ominus$. The star Alderbaran has radius of $40R_\ominus$ and Antares has that of 700 $R_\ominus$.

Unit of measurement of size
1 solar radius, R = 7×10^{8} m

(*c*) **Measurement of Mass**

Solar Mass M_0 is the usual unit for measuring stellar masses. Now, $M_\ominus = 2 \times 10^{30}$ kg. Thus, Mass of Milky Way gallaxy is about 10^{11} $M_\ominus$. Also mass of a globular cluster is to the tune of $10^{5} - 10^{6}$ M.

Indian scientist S. Chandrashekhar proved that the mass of a white dwarf cannot exceed 1.4 $M_\ominus$. This is known as the Chandrashekhar Limit.

Unit of measurement of mass
1 solar mass M = 2×10^{30} kg

(*d*) **Time Scale**

At present the Sun is about 5 billion years old. In its today's form, the Sun is estimated to live for another 5 billion years. The galaxy is around 10 billion years. The universe itself might be 12 to 16 billion years. At the other end, when the pressure inside a star is not enough, the star may collapse in seconds.

(*e*) The following table shows distances, radii and masses of some stars and planets

Table 1.1: Distance, radii and masses of astronomical objects

	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

	Distance	Radius	Mass	Remarks
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, RADIANT FLUX AND LUMINOSITY

Objects in the space emit energy. Finding out how much energy each object emits is an important problem in astronomy. The emitted energy is measured in Luminosity, which is related to the radiant flux and brightness of the object.

It is a fact that a star may seem bright if it is closer to the Earth, and the same star may appear faint if it is far away. The apparent brightness of space objects can be estimated easily, but to measure real or intrinsic brightness of such objects, their distance has to be considered and accounted for.

The apparent brightness of a star is defined in terms of apparent magnitude of that star.

(*a*) Apparent Magnitude

In the west the greek astronomer Hipparchuns was the first astronomer to classify the stars that were visible to the naked eye. He put them into six classes on the basis of their apparent magnitudes or relative brightness as seen from the earth. He prepared a scale of Apparent Magnitude (m) ranging from M_1 (the brightest) to M_6(the least bright).

Definition of Apparent Magnitude (M)

Apparent Magnitude of an astronomical object is a measure of how bright it appears on the Magnitude scale. A smaller magnitude (M) means a brighter star.

(*b*) Magnitude Scale is Logarithmic

The magnitude scale is a non-linear scale. This means if a star is two magnitudes fainter than another star it is not twice as faint. In fact, it is 6.3 times fainter. This fact can be explained as follows.

The response of human eye to increasing brightness is almost logarithmic. We thus want a suitable logarithmic scale for magnitudes on this scale. A difference of 5 Magnitudes should be equal to a factor of 100 in brightness. Hence, on such a scale, the brightness ratio for 1 magnitude difference is $100^{1/5}$ or $2.5118 \simeq 2.512$.

This way, a star with magnitude 1 is 2.512 times brighter than a star of magnitude 2. For a star of magnitude 3 (i.e. difference of 2 in magnitudes) the star with Magnitude 1 is as brighter $(2.512) \times (2.512) = (2.512)^2 = 6.31$ times . Similarly it is $(2.512)^3 = 15.851 \simeq 16$ times brighter than a star of magnitude 4, and $(2.572)^4 = 39.818 = 40$ times brighter than a star of magnitude 5. Also, a star with magnitude 1 is $(2.512)^5 = 100.02 = 100$ times brighter than a star with magnitude 6.

Example: The Pole Sar (Dhruva, ध्रव, Plaries) has an apparent magnitude of +2.3 and the star Altair has apparent magnitude of 0.8. Hence, Altair is $(2.512)^{2.3-0.8} = (2.512)^{1.5} = 3.982 \simeq 4$ times brighter than Pole Star.

(*c*) Mathematical Expressions

Let b_1 = brightness of first star
b_2 = brightness of second star
M_1 = Magnitude of first star
M_2 = Magnitude of second star

Then, the relationship between the brightness and magnitude of the two stars is governed by following formula:

$$M_1 - M_2 = 2.5 \log_{10}\left(\frac{b_2}{b_1}\right)$$

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

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

(*d*) Brightness Ratio for given Magnitude Difference

Table 1.2 below gives brightness ratio for various magnitude differences.

Magnitude Difference	Brightness Ratio
0.0	1.0
0.2	1.2
1.0	2.5
1.5	4.0
2.0	6.3
2.5	10.0
3.0	16.0
4.0	40.0
5.0	100.0
7.5	1000.0
9.0	3982.0
10.0	10000.0

(*e*) Modern Day Scale of Brightness

Today, modern astronomers use a similar scale for apparent magnitude with ultra tech telescopes many fainter than 6th magnitude and brighter than 1st magnitude stars have been observed.

Therefore, zero and even negative magnitudes are now part of the scale. Thus, a star of magnitude – 1 is 2.512 times brighter than a star of zero magnitude. For us, Sirius A is the brightest star, apart from the Sun. Its apparent magnitude is –1.47 and brightness ratio is 9.72 = 10.

> Larger magnitude on negative scale indicates higher brightness and that on positive scale means more and more faintness of an object.

Currently, the faintest observed (and detectable) object in the space by a modern telescope has magnitude M = 29. It is fainter by 1.587 × 10^{11} times compared to a star with M = 1.

Sun has apparent magnitude M = –26.81. It is therefore $(2.512)^{1-(-)\,26.81} = (2.512)^{27.81} = 1.33 \times 10''$ times brighter than a star with apparent magnitude of M = 1. Also, Sun is brighter than the faintest known star with M = 29 by $(2.512)^{29-(-26.81)} = (2.512)^{55.81} = 2.114 \times 10^{22}$ times.

(*f*) Table of Apparent magnitudes (Table 1.3)

Object	Indian Name	Aparent 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

Let us now apply these ideas to a concrete example.

Example 1: Comparison of Brightness

Compare the brightness of the Sun and α-Centauri using the apparent magnitudes listed in the Table above

Sol. From above table,

$$m_{\text{Sun}} - m_{\alpha\text{C}} = -26.81 - (-0.10)$$
$$= -\,26.71.$$

Therefore, using Eq. (1.2), we obtain

$$\frac{b_{\alpha C}}{b_{Sun}} = 100\text{–}(26.71)/5 = 10^{-10.7}$$

or

$$\frac{b_{Sun}}{b_{\alpha C}} = 10^{10.7}$$, i.e. the Sun is about 10^{11} times brighter than α-Centauri.

Radiant Flux and Luminosity of a star

Even if we know the apparent magnitude and brightness of a star, they are not enough to help us in knowing the total energy emitted per second by the star. The knowledge can be obtained using the radiant flux and luminosity values of a star.

> **Definitions of Luminosity and Radiant Flux**
>
> Luminosity of a body is defined as the total energy emitted by it per unit time. Radiant flux is the total amount of energy flowing through per unit time per unit area of surface oriented normal to the direction of propagation of radiation

The unit of radiant flux is erg s^{-1} cm^{-2} i.e. erg per second per square centimetre area. Unit of luminosity is erg s^{-1} i.e. erg per second.

The erg system of units used in astronomy can be easily converted to SI units. The radiated energy from a body here includes both visible light as well as wave lengths.

(*a*) Two Factors on which radiant flux depends

The radiant energy of any source can be directly related to following two factors:

1. Radiant energy emitted by it.
2. Distance of the Source from the point of observation.

(*b*) Formulae for Radiant Flux and Luminosity

Let *r* = distance of a star from Earth. Now if we draw an imaginary sphere of radius *r* with the star at its centre, the surface are of the sphere would be $4\pi r^2$. And the Radiant flux F of the star in terms of its Luminosity L can be expressed as follows:

$$F = \frac{L}{4\pi r^2} \qquad \ldots(1)$$

The luminosity of star is the measure of its intrinsic brightness. It is mostly written in units of the solar luminosity, L_0, where

$$L_0 = 4 \times 10^{26}\ \text{W}$$
$$= 4 \times 10^{33}\ \text{erg s}^{-1}$$

(W = watts, 1 watt = 10^7 erg s^{-1})

Example: The luminosity of our Milky Way galaxy is about 10^{11} L_0.

(*c*) Ratio of Radiant Fluxes

Clearly the energy from a source received at any spot, decides the brightness of that source. This means radiant flux F is dependent upon the brightness B of the source. Brightness source gives larger radiant flux at a place. Hence, in place of ratio of brightness we can use ratio of radiant flux from two bodies at the same place. This means

$$\text{Ratio of fluxes } \frac{F_2}{F_1} = 100^{(m_1 - m_2)/5} \qquad \ldots(2)$$

Now, from equation (1) we know that flux received at a place also depends upon its distance from the source. That is why two stars with same apparent magnitude may not be equally luminous, their distances from the point of observation being different.

In fact, a star's apparent brightness may be known, but that gives no information about its luminosity. For that a true or intrinsic brightness measure of a star is required.