Demonstrations: none
Text: Mod. Phys. 7.A, 7.B, 7.C
Problems: 3, 4, 5 from Ch. 7

What's important:
•distances to stars and galaxies
•parallax
•luminosity

Planets, stars, galaxies and all that

Distance scales to stars and galaxies are huge, and we introduce two length units that are more appropriate than km:

light-year (ly) = 9.46×10^{12} km
parsec (pc) = 3.26 ly.

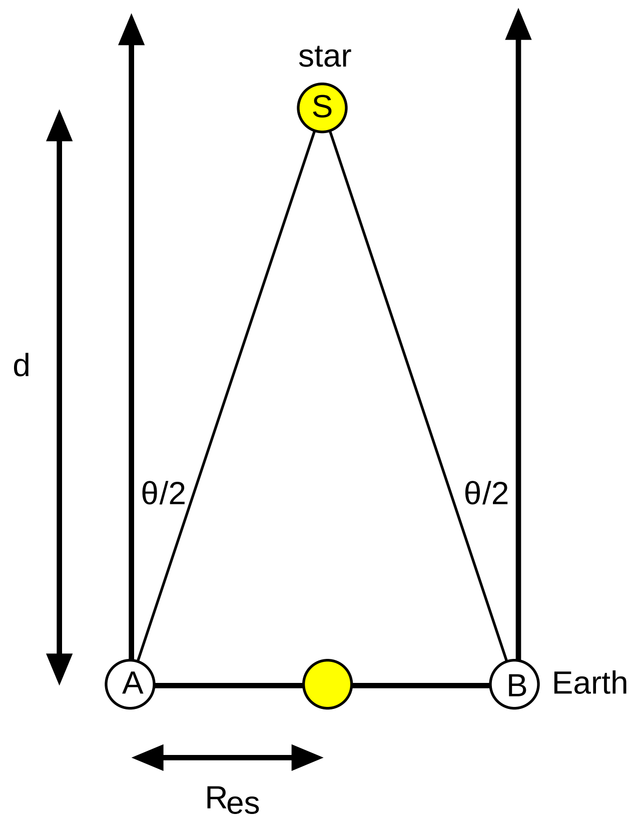
Our own galaxy, the Milky Way, consists of roughly 100,000,000,000 or 10^{11} stars. The Milky Way is about 50,000 ly in radius, and our solar system lies some 30,000 ly from its centre. The number of galaxies in our Local Group of galaxies is more like 30, and the nearest members of the Local Group, the Magellenic Clouds, are about 170,000 ly away. Some distance scales:

Quantity	km	ly (1 ly = 9.46×10^{12} km)
radius of Earth	6.4×10^{3}	6.8×10^{-10}
radius of Sun	7.0×10^{5}	7.4×10^{-8}
distance from Sun to Earth	1.50×10^{8}	1.58×10^{-5}
distance from Sun to Pluto	5.9×10^{9}	6.3×10^{-4}
distance to nearest star	4.0×10^{13}	4.27
Sun to centre of Milky Way	2.8×10^{17}	30,000
radius of Milky Way	4.7×10^{17}	50,000
distance to nearest galaxy	1.6×10^{18}	170,000
distance to galaxies in Hydra	4×10^{22}	4,000,000,000
furthest object detected	$> 10^{23}$	>10,000,000,000

There are several techniques used to determine distances to stars, including:
•the apparent motion of nearby stars (parallax)
•the apparent luminosity of stars

Parallax

Knowing the radius of the Earth's orbit, distances to nearby stars can be found through parallax, the apparent motion of nearby stars caused by the motion of the Earth in its orbit around the Sun (first used in 1838 by Freidrich Wilhelm Bessel).



The Earth is shown in its orbit at two extreme positions 6 months apart, labelled by the letters A and B, and a nearby star is at position S. The direction towards a very distant star is indicated by the two vertical lines with arrows at their tips. The distant star provides a reference point against which closer stars appear to move. At position A, the star S appears to lie to the right of the fixed background by an angle $\theta/2$. Six months later, owing to the orbital motion of the Earth, the star appears to lie to the left of the fixed background by $\theta/2$. The angle $\theta/2$ is referred to as the **parallax** of the star.

From trigonometry,

$$\tan(\theta/2) = \mathbf{R}_{es} / \mathbf{d}$$

where $\mathbf{R}_{es}$ is the radius of the Earth-Sun orbit and $\mathbf{d}$ is the perpendicular distance of the star from the orbital diameter. (*Note*: the star need not be perpendicular to the plane of the Earth-Sun orbit; the maximum apparent change in the remote star's position will be described by the figure irrespective of the tilt in the Earth's orbit with respect to the star's position.) In practice, $\mathbf{d} \gg \mathbf{R}_{es}$, hence, we use

$$\tan(\theta) \rightarrow \theta \qquad \text{as } \theta \rightarrow 0,$$

to obtain

$$\mathbf{d} = 2\mathbf{R}_{es} / \theta \quad (\theta \text{ in radians})$$

The further away a star is (*i.e.*, large $\mathbf{d}$) the smaller θ is. Astronomical measurements of parallax may be quoted in terms of arc seconds:

1 arc second = 1/60 of an arc minute = 1/3600 of a degree

If there are 180 degrees for every π radians, then

648000 arc seconds = π radians
or
1 arc sec. = (π / 648,000) radians

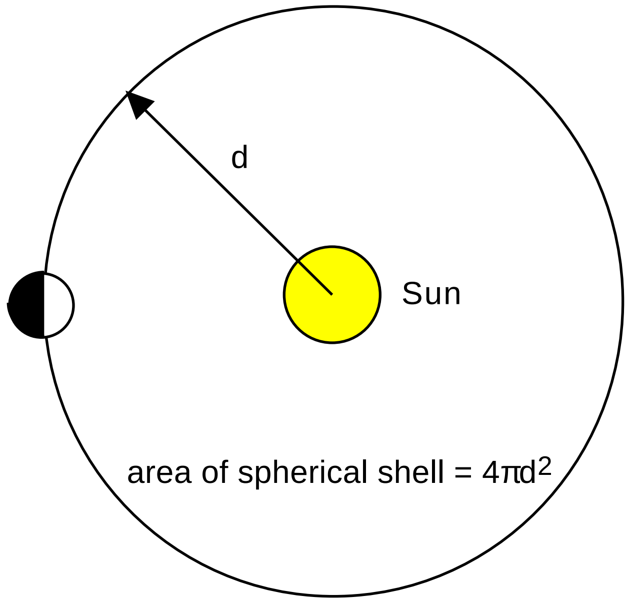
The value of $\mathbf{d}$ corresponding to $\theta/2$ of exactly 1 arc second is called the parsec (from parallax second):

$$\mathbf{d} = 2\mathbf{R}_{es} / \theta = 1.58 \times 10^{-5} / (\pi / 648{,}000) = 3.26 \text{ l.y.}$$

There is a lower limit to the minimum parallax that can be detected, and this places an upper limit on how far away a star's position can be deduced using parallax. Currently, parallax is useful as a technique only for stars within about 300 ly of Earth.

Luminosities and distances to stars

The total energy emitted from the surface of a star per unit time (which is the total power of the star) is referred to as its **luminosity L**. The luminosity of the Sun, for example, is 3.9×10^{26} J/s (or watts). The amount of energy from the Sun that reaches a particular planet depends on the distance of the planet from the Sun, since solar energy is emitted in all directions and spreads throughout space. By the time the solar radiation reaches a distance $\mathbf{d}$ from the Sun, it has been spread over an area of $4\pi\mathbf{d}^2$, as illustrated:



The amount of energy per unit time crossing an element of area facing the Sun, but a distance **d** away from it, is referred to as the flux **f.** In terms of the luminosity, the flux is given by:

$$\mathbf{f} = \mathbf{L} / 4\pi\mathbf{d}^2$$

and has units of energy per unit area per unit time. Further, there is nothing special about the Sun in this equation, it applies to all stars.

<u>Example</u>

The solar luminosity is 3.9×10^{26} J/s, and the corresponding energy flux from the Sun as seen on the Earth (a distance of 1.5×10^{11} m away) is 1400 watts / m^2.

If one can determine the luminosity of a star WITHOUT knowing **d**, then a measurement of the flux **f** can be inverted to find **d**. That is:

(i) extract **L** from some observable of the star
(ii) measure **f** on Earth
(iii) use $\mathbf{f} = \mathbf{L} / 4\pi\mathbf{d}^2$ to solve for **d**.

Two methods used to find **L**:

(i) **L** is related to surface temperature for many stars

Light emitted from a hot object has a distribution of wavelengths that is specific to the object's temperature. For example, while the Sun emits an abundance of light throughout the visible spectrum, a heating element on a stove is more likely to appear red even at its hottest. Most stars have surface temperatures in the 2,500 to 30,000 ^{o}K range, with the Sun having a surface temperature of 5,800 ^{o}K.

The luminosities of nearby stars can be determined accurately since their positions are known from parallax, and we find that the luminosity of young stars increases steadily with their temperature.

The problem with this approach is that dust and gas between Earth and the star in question tend to reduce **f** and give a calculated distance that is longer than the true distance.

(ii) **L** is related to the pulsation period of Cepheid variables

Cepheids are stars whose luminosity oscillates with periods of roughly 1 to 50 days. Earlier this century, astronomer Henrietta Leavitt established that Cepheid luminosity is a unique function of the oscillation period, through her studies of nearby Cepheids with well-determined distances. The Cepheid variables are members of what astronomers refer to as **standard candles**, used to determine the distance to remote objects that show no measurable parallax.