Distances in the Solar System

- Distance to Venus can be obtained using *radar ranging*
- Send signal, determine how long it takes to return
- Radio waves move at the speed of light, which is known \( (3 \times 10^8 \text{ m/s}) \)
- Calculate distance:

\[
\text{distance} = \text{(speed of light)} \times \left( \frac{\text{time taken for signal to return}}{2} \right)
\]

- Can use this to accurately measure Earth-Sun distance:
- Measure distance to Venus at *greatest elongation*, i.e. when Venus appears furthest from the Sun, as seen from Earth:

\[
\text{Earth - Sun distance} = \frac{\text{Earth - Venus distance}}{\cos \theta}
\]

- Here, \( \theta \) is the Sun-Earth-Venus angle at greatest elongation
- Earth-Sun distance = \( 1.49598 \times 10^{11} \text{ m} \)
  or 1 Astronomical Unit (AU)

\[
\bigcirc = \text{Sun} \quad \bigodot = \text{Venus} \quad \oplus = \text{Earth}
\]

Distances to Nearby Stars – Parallax

- Parallax occurs when viewing an object from two different positions; the object will appear to move with relative to the background
- As Earth moves around the Sun in its orbit, nearby stars will seem to move back and forth relative to background stars
- *Parallax angle* (\( \theta \) below) is half the difference in angle between the two points of view (6 months apart):

\[
\sin \theta = \frac{1 \text{ AU}}{\text{distance to star}}, \text{ So that:} \quad \text{distance to star} = \frac{1 \text{ AU}}{\sin \theta}
\]

- The further away a star is, the smaller the parallax angle
• New unit: parsec (pc)
• If you were a parsec away from Earth, then the Earth-Sun distance of 1 AU would subtend an angle of 1 arcsecond
  (1 arcsecond is 1/3600 of a degree; smaller than the angle made by a grain of sand held at arm’s length)
• Or, the parallax angle of a hypothetical object at a distance of 1 pc would be 1 arcsecond:

\[
1 \text{ arcsecond} = \frac{1}{3600} \text{ deg, so:}
\]

\[
D = \frac{1 \text{ AU}}{\sin(\frac{1}{3600})} = 206265 \text{ AU} = 3.1 \times 10^{16} \text{ m}
\]

\[
= 1 \text{ parsec (pc)}
\]

• This leads us to a simple formula. If we know the parallax of a star in arcseconds, then we automatically know its distance from the Solar System in parsecs:

\[
D(\text{pc}) = \frac{1}{\rho(\text{arcsec})}
\]

The Magnitude Scale

• Luminosity of a star = amount of energy star radiates into space per second
• Apparent brightness = amount of energy received from star at Earth per second, per square metre = how bright an object is as seen from Earth
• So apparent brightness depends on luminosity and distance of star – inverse square law:

\[
\text{brightness} = \frac{\text{luminosity}}{4\pi(\text{distance})^2}
\]

• Astronomers usually use the magnitude system:
• Apparent brightness is related to apparent magnitude \(m\) as follows (subscripts 1 and 2 refer to two different objects – we compare two objects for definition):

\[
m_1 - m_2 = -2.5 \log \left( \frac{\text{brightness}_1}{\text{brightness}_2} \right)
\]
• A difference of 5 in apparent magnitude equals 100 times in brightness
• Here are some familiar objects on the magnitude scale. Remember that brighter objects have smaller values for magnitude!

\[
\text{Sun} (-26.7) \\
\text{Full moon} (-12.6) \\
\text{Venus (at brightest)} (-4.4) \\
\text{Sirius (brightest star)} (-1.4) \\
\text{Naked eye limit} (+6.0) \\
\text{Binocular limit} (+10.0) \\
\text{Pluto (+15.1)} \\
\text{Large telescope (visual limit) (+21.0)} \\
\text{Hubble Space Telescope and large Earth-based telescopes (photographie limit) (+30.0)}
\]

• Just as astronomers use apparent magnitude instead of brightness, instead of luminosity, they use **absolute magnitude** \((M)\)
• Absolute magnitude = *the apparent magnitude of an object at a distance of 10 parsecs*
• Apparent magnitude and absolute magnitude of an object are related by the following:

\[
m - M = 5 \log(\text{distance}) - 5
\]

where the distance here is given in parsecs.

• So, if we can know the absolute magnitude (or luminosity) of an object, *we can calculate the distance to the object*, since we have measured its apparent magnitude (apparent brightness)!

### The Milky Way and Beyond – Standard Candles

• Analogy: car headlights
• If you measure the brightness of a car’s headlights at different distances, you will obtain different values
• However, we know how the headlight behaves, regardless of the distance, i.e. we know its luminosity.
• We can then determine its distance, since we know both its apparent brightness and luminosity.
• Objects in astronomy such as these, for which we already know their luminosities, or absolute magnitude, are called **standard candles**
• There are two main types of standard candles that are used by astronomers: **Cepheid variables stars** and **type Ia supernovae**
Cepheid Variable Stars

- Stars in particular stage of their evolution, in which the star will expand and contract with a certain period
- This causes the luminosity of the star to continuously rise and fall

- It turns out that the average luminosity of a Cepheid variable star depends on its pulsation period (how long it takes to expand, contract, and expand again)

- So, if we measure the star’s pulsation period, we will automatically know its luminosity, or absolute magnitude
- That, along with the apparent magnitude, which we measure directly, gives us the distance to the star

- The fact that Cepheid variable stars are very bright makes them very useful – we can see them in other nearby galaxies, and thus measure the distance to such galaxies!

- The reason we know the actual luminosities of these stars is because we have measured the distances to various Cepheid variables within the Milky Way, close to Earth, using parallax! Then calculation of the luminosity (or absolute magnitude) of many close-by Cepheid variables is possible once we know the star’s brightness (or apparent magnitude) and distance, allowing us to compare them to the more distant Cepheid variable stars

Type Ia Supernovae

- Supernova: stellar explosion
- In a fraction of a second, releases 100 times as much energy as the Sun does over its entire 10 billion year life!
- Two main types:
  - Type II supernovae occur for stars greater than 3 times the mass of the Sun; eventually, the star will lose its battle against gravity, and collapse, which will cause the explosion of the star, leaving behind a neutron star or a black hole, depending on how massive the star initially was.
  - Type II supernovae do not make good standard candles – their luminosities can vary depending on the mass of the star that is collapsing, which is not known
• *Type Ia supernovae* occur when a white dwarf star (the last stage of evolution for a Sun-like star, under 3 solar masses) accretes matter, possibly from a companion star in a binary system.

• Once the white dwarf crosses a mass threshold known as the *Chandrasehkar mass* limit – 1.4 times the mass of the Sun – the star will explode, and leave nothing behind, undergoing complete and total disruption.

• Since the white dwarf is always this Chandrasehkar mass when it explodes, the peak *luminosity* (the luminosity when the supernova is at its brightest) is predictable, unlike the case of the type II supernova.

• Thus the type Ia supernovae make good standard candles.

• The other good thing about type Ia supernovae is that they are extremely bright, allowing us to see them in, and get the distances to, very distant galaxies.

• We know the luminosities of type Ia supernovae by measurements of the distances to nearby galaxies, within which these supernovae occur, using *Cepheid variable stars*. Again, using their distances and apparent brightnesses, we obtain the luminosities of several of these close-by supernovae, which we can then compare to distant type Ia supernovae.

### The Hubble Diagram

• In 1924, Edwin Hubble measured the distance to the Andromeda “nebula”, using Cepheid variable stars.

• He found that Andromeda is located *outside* the Milky Way! It was actually an entire galaxy of its own, just like the Milky Way!

• He then went on to measure the distances to several galaxies.

• He could have stopped there and solidified his place in the history of astronomy, but Hubble then proceeded to measure the *velocities* to several galaxies using the observed *Doppler shift* of the galaxies’ spectra.

• When Hubble plotted the velocities of the galaxies against their measured distances, he found something very interesting and completely unexpected (the graph to the right is actually the original plot made by Hubble – this type of plot is generally known as a *Hubble diagram*).

• It showed that the further away a galaxy was from us, the faster it was moving away from us!
• This is due to the expansion of the Universe!
• This is summarized in an equation known as Hubble’s law:

\[
\text{velocity} = H_0 \times \text{distance}
\]

• \(H_0\) is called Hubble’s constant, and is now more or less agreed upon as being approximately 75 km/s/Mpc. This means that for every million parsecs you look farther away, the galaxy you are observing will appear to be moving away from you 75 km/s faster.

• This allows the Hubble diagram itself to be used as a distance indicator!
• Take the more recent Hubble diagram to the right as an example, created using type Ia supernovae (the little box in the bottom left corner of the plot is the limits of the original diagram made by Hubble)
• If you measure a galaxy with a velocity of about 39,000 km/s, then its distance should be around 600 Mpc from us

• However, recent measurements of even more distant type Ia supernovae point to the fact that the expansion of the universe is not so constant after all, meaning the Hubble diagram only results in a straight line for very nearby galaxies

• Remember that the further away from Earth you are looking, the further back in time you are looking as well. This is because the speed of light is a maximum speed, and so it takes time for the light to arrive at Earth.
• Therefore, the light you observe from a distant galaxy or supernova tells you how it looked many, many eons ago

• Research groups such as the Supernova Cosmology Project have shown that the light from these far-away type Ia supernovae is taking longer to arrive at Earth than expected, as shown in the diagram to the right (the dashed box represents the limits of the last Hubble diagram shown)
• Results from other types of observations tell us that this is probably not because the supernovae are different back then, or because there is dust obscuring our observations, making the supernovae look as if they are further away.

• It seems that the answer is that the Universe is actually *accelerating* in its expansion today, stretching the Universe at a faster and faster rate! This would cause the light to take longer to reach us than expected.

• No one really knows the cause of this acceleration. It is attributed to a mysterious force which is simply called *dark energy*.

• Dark energy is the subject of a great deal of scientific research today, and is currently one of the hottest topics in astronomy.
A Couple of Problems

1. This problem deals with parallax calculations:
   a. How far away, in units of parsecs, is a star that has a measured parallax angle of 2 arcseconds?
   b. The parallax of the closest star to Earth, Proxima Centauri, is 0.772 arcseconds. How far away is Proxima Centauri from Earth, in units of parsecs?

2. This problem deals with the magnitude scale:
   a. The apparent magnitude of the Sun is –26.7. The apparent magnitude of Sirius, the brightest star in the night sky, is –1.4. How much brighter is the Sun than Sirius, as seen from Earth?
   b. Through parallax measurements, Sirius is found to be a distance of 2.6 pc from Earth. What is its absolute magnitude?
Answers to Problems

1. For both parts, we use the following formula:

\[ D(\text{pc}) = \frac{1}{p(\text{arcsec})} \]

a. If a star has a parallax of 2 arcseconds, its distance would then be:

\[ D(\text{pc}) = \frac{1}{2} = 0.5 \text{ pc} \]

The star would be 0.5 pc from Earth. This is only hypothetical of course, since Proxima Cenauri is further away than this and it is the closest star to Earth.

b. Proxima Centauri has a parallax of 0.772 arcseconds, so its distance is then:

\[ D(\text{pc}) = \frac{1}{0.772} = 1.30 \text{ pc} \]

Proxima Centauri is 1.30 pc from Earth.

2. a. \( m_{\text{Sun}} = -26.7 \), \( m_{\text{Sirius}} = -1.4 \):

We use the following formula to get the brightness ratio:

\[ m_{\text{Sun}} - m_{\text{Sirius}} = -2.5\log \left( \frac{\text{brightness}_{\text{Sun}}}{\text{brightness}_{\text{Sirius}}} \right) \]

Which we can rearrange to become:

\[ \frac{\text{brightness}_{\text{Sun}}}{\text{brightness}_{\text{Sirius}}} = 10^\frac{m_{\text{Sun}}-m_{\text{Sirius}}}{-2.5} \]

\[ = 10^{\frac{-26.7-(-1.4)}{-2.5}} \]

\[ = 1.3 \times 10^{10} \]

The Sun is 13 billion times brighter than Sirius, the brightest star in the night sky, as seen from Earth.
b. We know that $m_{\text{Sirius}} = -1.4$ and that $D_{\text{Sirius}} = 2.6$ pc. We use the formula:

$$m - M = 5\log(\text{distance}) - 5$$

which we can rearrange to become:

$$M = m - [5\log(\text{distance}) - 5]$$

and so:

$$M = -1.4 - [5\log(2.6) - 5]$$

$$= 1.5$$

Therefore, Sirius has an absolute magnitude of 1.5.