Lectures 1-2 - The Big Picture

What's important:
- course outline
- distance scale
- parallax

Text: Carroll and Ostlie, Sec. 3.1

Pedagogically, astrophysics can be approached from many different directions, each of which selects particular topics for presentation. With less emphasis on observational astronomy, this course focuses on stellar evolution and the origin of the universe, with brief excursions into planet formation. Although we review the fundamental physics needed for the course, in some cases the treatment is brief, where the material has already been treated in PHYS 120 (Modern Physics and Mechanics) or PHYS 285 (Introduction to Relativity and Quantum Mechanics).

Textbooks

Recommended:

Bradley W. Carroll and Dale A. Ostlie *An Introduction to Modern Astrophysics*
http://astrophysics.weber.edu

Review of elementary particles is on-line in the PHYS 120 website.

Supplementary:

Steven Weinberg *The First Three Minutes: A Modern View of the Universe*
Donald D. Clayton *Principles of Stellar Evolution and Nucleosynthesis*
P.J.E. Peebles *Physical Cosmology*

Marking

• 2 midterms	40%
• 6 assignments	10%
• Final exam	50%

Rough outline
- Overview: the stars observed; mechanics of orbits
- Planets: sources of planetary material; planets in the solar system; atmospheres
- Stellar evolution: Hertzsprung-Russell diagram; stellar temperatures
- Thermonuclear reactions: velocity distribution; tunnelling, cross sections
- Hydrogen burning: PP chains and CNO bi-cycle
- Stability of stars: radiation pressure; gravitational collapse; stellar lifetimes
- Degenerate matter; white dwarfs and neutron stars
- Galaxy formation
- Dark matter: Keplerian orbits; speed-distance relation
- Cosmology: Hubble's law; microwaves; the early universe; ^{4}He production; open or closed universe?

The Big Picture

Distance scales to stars and galaxies are huge by terrestrial standards, requiring larger units of length than km:

light-year (ly) = $3.0 \times 10^8 \cdot \pi \times 10^7 = 9.46 \times 10^{15}$ m = 9.46×10^{12} km

parsec (pc) = 3.26 ly (see below).

Distances around the solar system are often quoted in Astronomical Anits (AU)

1 AU = 1.4960×10^8 km

which is a standard equivalent to the Sun-Earth distance.

Our own galaxy, the Milky Way, consists of roughly 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. Examples:

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

Measurements of sizes and distances

Several techniques are used to determine distances to stars, including:

- the apparent motion of nearby stars (parallax)
- the apparent luminosity of stars.

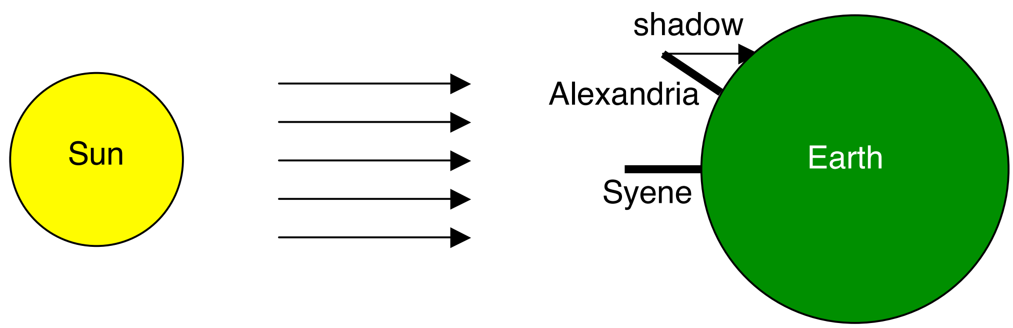
Here, we will review some historical aspects of distance measurements first, then describe parallax and finally luminosities (lecture #3).

Historical

Radius of the Earth, R_e

Aristotle [384-322 BC] and some of his predecessors recognized that the Earth was round by observing lunar eclipses, in which the shadow cast by the Earth is always seen to be an arc of a circle, independent of the local time of day of the eclipse (the local time of day would correspond to a different orientation of the plane of the Earth, if the Earth were flat). Note that the shadow cast by the Earth varies with the orientation of the Moon's orbit to that of the Earth around the Sun: if the orbits were co-planar, there would be a solar and a lunar eclipse every 4 weeks.

The first "absolute" measurement of an astronomical distance was the radius of the Earth, performed by Eratosthenes of Alexandria (*ca*. 276 to *ca*. 195 BC), who used shadows to determine the Earth's radius. It was known that the Sun was directly overhead at the Egyptian town of Syene on a particular day – the Sun cast no shadow in a deep well. Aristarchus reasoned that if he could determine the length of a shadow at a different location but the same time of day, he could obtain the radius of the Earth.



The measurement was done at the city of Alexandria on the Mediterranian Sea: a tall pole at Alexandria cast a shadow of 7° (0.12 radians) off the vertical, which is 1/50th of a complete circle. Thus:

[*Syene-Alexandria distance*] / [*circumference of Earth*] = 1/50.

Part of the difficulty in assessing the accuracy of Eratosthenes' measurement lies in converting the historical length unit of the time (stade) into meters; estimates of the stade yield the circumference to be 42,000 km in modern units, about 5% above the true value.

Distance from Earth to Sun, R_{es}

This distance was also known to the Greeks, although not very accurately because of the uncertainty in one component (#3 below) of the measurement. One can calculate four unknowns in terms of R_e:

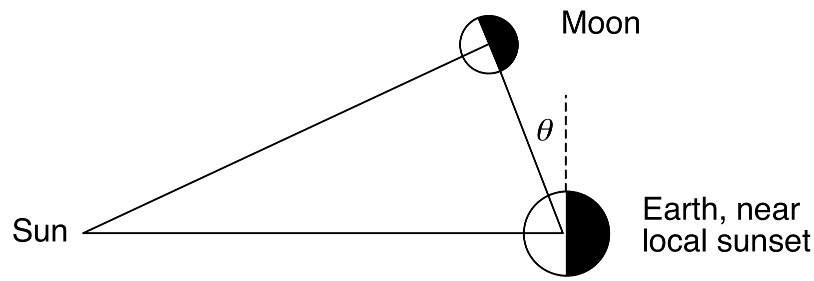
R_{es} = Earth-Sun distance R_{em} = Earth-Moon distance
R_s = radius of the Sun R_m = radius of the Moon

This was first done before 200 BC by Aristarchus of Samos (310 to ~230 BC), athough it took Eratosthenes' measurement of the Earth's radius to convert the measurements to terrestrial units.

1. Angular size of the Sun gives $2R_s$ / R_{es} (modern = 0.0093 radians = 1.39 x 10^6 / 1.5 x 10^8 in km)

2. Angular size of the Moon gives $2R_m$ / R_{em} (modern = 0.0091 radians = 3476 / 3.84 x 10^5 in km)

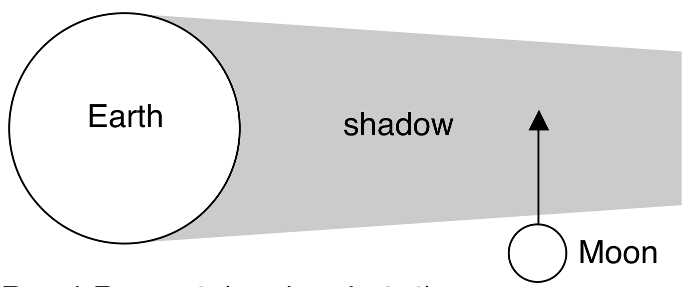
3. Measuring the deviation from vertical (a few degrees) of the position of the Moon when it is exactly half illuminated. Looking down on the Earth-Moon-Sun plane:



From the measured value of θ (not easy, Aristarchus measured 3°), one can obtain the ratio R_{es} / R_{em} from

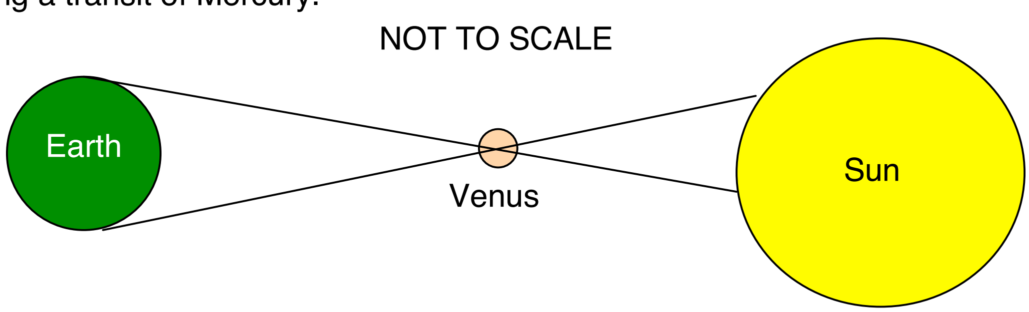
$$R_{es} = R_{em} / \sin\theta$$

4. Measurement of the apparent size of the Earth's shadow in a lunar eclipse.



Aristarchus found R_{earth} / R_{moon} ~ 3 (modern is 3.4).

The Sun-Earth distance was determined more accurately in 1761, when the Royal Astronomer Halley (of comet fame) used the transit of Venus "across" the Sun as a parallax measurement. Halley had proposed this technique many years earlier after observing a transit of Mercury.



Modern measurements of the distance to the Sun can use pulse-echo techniques. The

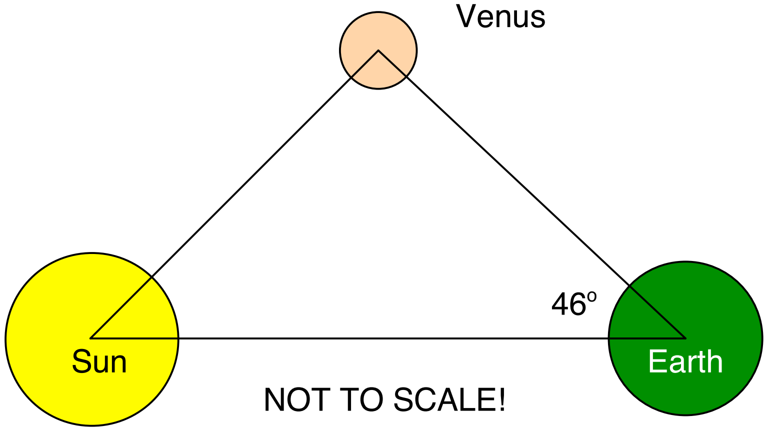
Earth-Sun distance is defined as the Astronomical Unit (AU) and has a modern value of

$$1 \text{ AU} = 1.4960 \times 10^8 \text{ km}$$

Orbital radii

The first calculations of the relative sizes and distances among the Earth, Sun and Moon were done by Aristarchus. His work proved not to be overly accurate, but established that these quantities were measurable. Aristarchus also proposed a heliocentric theory some 1800 years before Copernicus, with the corresponding notion that the Earth rotated around its axis.

The angular size of planetary orbits can be measured (visually for many planets), and these can be converted to AU with a heliocentric model. For example, the greatest angular distance of Venus from the Sun is 46°, which can be interpreted by



$$R_{\text{sun-venus}} = R_{\text{sun-earth}} \sin 46^\circ$$

or

$$R_{\text{sun-venus}} = 0.72\ R_{es} = 0.72 \text{ AU}$$

There is a similar calculation for the outer planets, but it requires the orbital periods. From these trigonometric results, we find (modern)

Planet	orbital radius (AU)
Mercury	0.387
Venus	0.723
Earth	$\equiv 1$
Mars	1.523
Jupiter	5.203
Saturn	9.539

Note: as an alternative, once one orbit is known, the rest can be found by measuring the orbital period and invoking one of Kepler's laws:

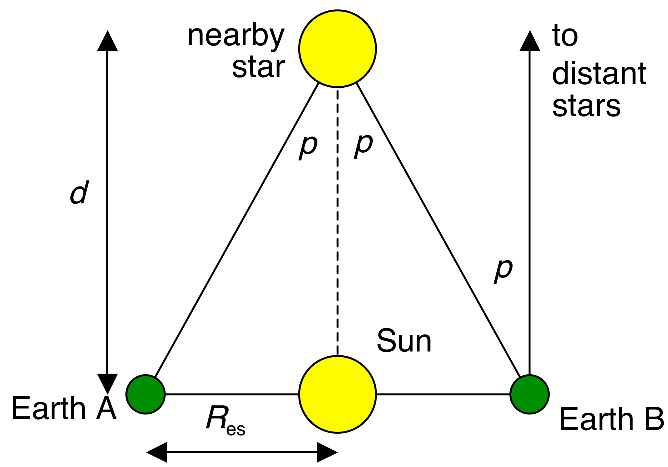
$$R^3 / T^2 = GM_{sun} / 4\pi^2$$

using the known orbit to fix GM_{sun}.

Parallax

Knowing the radius of the Earth's orbit R_{es}, 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).

Below, 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 p. Six months later, owing to the orbital motion of the Earth, the star appears to lie to the left of the fixed background by p. The angle p is referred to as the **parallax** of the star.



From trigonometry,

$$\tan(p) = R_{es} / d$$

where R_{es} is the radius of the Earth-Sun orbit and 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, $d >> R_{es}$, hence, we use

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

to obtain

$$d = R_{es} / p \quad (p \text{ in radians})$$

The further away a star is (*i.e.*, large d) the smaller p 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

π radians = 180 degrees = 180 • 3600 arc secs = 648000 arc secs

or

1 arc sec = (π / 648,000) radians

The value of d corresponding to p of exactly 1 arc second is called the parsec (from parallax arc second):

$$d = R_{es} / p = 1.58 \times 10^{-5} / (\pi / 648{,}000) = 3.26 \text{ ly}$$

or

$$= 1.496 \times 10^{8} / (\pi / 648{,}000) = 3.09 \times 10^{13} \text{ km}$$

To quote distances in parsecs, one just takes the reciprocal of p

d (in parsecs) = 1 / p (in arc seconds).

Distances to stars

- First measurement of a distance to a star using parallax was made in 1838 by Bessel for the star 61 Cygni:
  $p = 0.316$ arc seconds
  $d = 1 / 0.316 = 3.16$ pc = 10.3 ly (modern value is 11.1 ly)

- closest star is Proxima Centauri
  $p = 0.77$ arc seconds
  $d = 1 / 0.77 = 1.30$ pc = 4.2 ly

- 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. Space-based telescopes can detect $p \sim 10^{-3}$ arc seconds, ten times better than typical resolution on Earth. This distance limit corresponds to
  $d = 1 / 10^{-3} = 10^{3}$ pc ~ 3000 ly (small compared to 30,000 ly to the galactic centre)