1 Introduction

1.1 Astronomy and Astrophysics

1.1.1 What distinguishes them? What are they?

Astronomy is

- the art of observation and the measurement side of the subject
- radio, optical, IR, UV, x-ray, γ-ray, neutrino, gravity-wave studies
- measure positions, brightnesses, spectra, structure of gas clouds, planets, stars, galaxies, globular clusters, clusters of galaxies, superclusters, quasars, etc.

Astrophysics is

- the application of physics to these observations to understand and interpret them
- the subject of this course

1.1.2 Characteristics of astrophysics

a) Large range of scales: from nuclear scales (1 fm $= 10^{-15}$ m $=$ 1 Fm $= 10^{-13}$ cm) to cosmological scales ($10\,\mathrm{Gpc} = 10^{10}\,\mathrm{pc} = 3 \times 10^{26}\,\mathrm{m} = 3 \times 10^{28}\,\mathrm{cm}$), a range $\sim 3 \times 10^{41}$. Some problems involve large and small scales; for example, the Chandrasekhar mass,

$$\begin{aligned} M_{Ch} \approx \frac{1}{m_p^2}\left(\frac{\hbar c}{G}\right)^{3/2} &= 3.7 \times 10^{33}\,\mathrm{g} \\ &\approx 2M_\odot \end{aligned}$$

involves small-scale physics ($\hbar$) and yet describes something with a mass about twice the mass of the Sun.

b) Systems are often complicated, and we cannot always conduct experiments to isolate the relevant variables/parameters. The observations that astronomy provides are often very inaccurate and incomplete, so we often need only work to low accuracy (order of magnitude calculations). A factor 2 error in the theory is excellent in some areas, a factor 10^2 is good in others. Sometimes the data are embarrassingly precise, and we have to do *much* better, e.g., in solar system studies.

c) Astrophysics covers a broad spread of physics, including topics that normally do not appear in a physics curriculum: e.g., fluid mechanics, magnetohydrodynamics, radiative transfer, etc. Many phenomena that *cannot* be reproduced in the laboratory occur in astrophysics (e.g., flux freezing, gravitational collapse), so astrophysical interpretations may offer the only paths to some parts of physics.

d) But note: we do *not* allow "new physics" to be involved very often. Astrophysics corresponds to an application of the *standard laws of physics* to the Universe as a whole. We assume the universality (literally) of the laws of physics in order to make any progress at all and to be *allowed* to call the subject "astrophysics"! The extent to which our laboratory laws extend to the distant objects in the Universe and provide explanations of phenomena there provides evidence for this point of view.

e) Astrophysics is intimately connected with what astronomy is *able* to observe. Until recently, there was little high-energy astrophysics because there was no high-energy (x-ray and γ-ray) astronomy. Now there is, and we can see much *hotter* parts of objects than we knew about before.

f) Astronomy and astrophysics generally assumes the Copernican principle:

WE ARE IN NO FAVORED POSITION IN THE UNIVERSE.

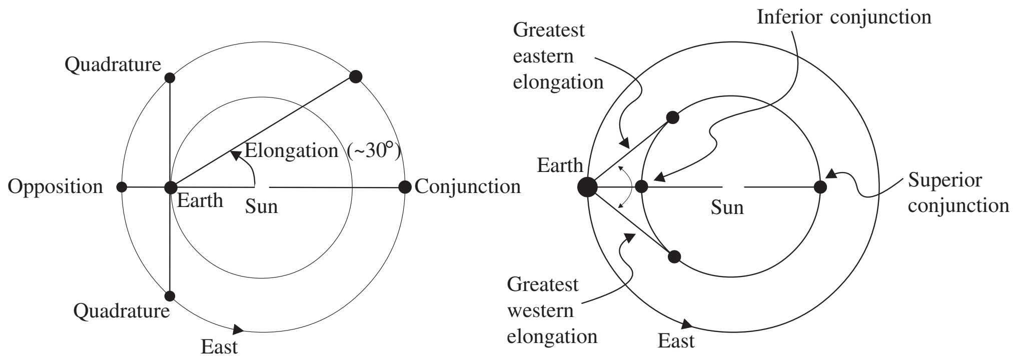
so the Universe near us and physics near us are *typical* of *contemporaneous* parts of the Universe — unless, of course, we find factual evidence to the contrary (and this should be, in each such case, only by rare good or bad luck.)

When does astronomy turn into astrophysics? No hard-and-fast line, but where *physical laws* (not just geometric arguments or logic) are applied.

1.2 Quick history of some pre-astrophysics discoveries

1.2.1 Copernicus gets Solar System geometry, but no scale

Copernicus (early 1500's!) measured the *relative* size of the planetary orbits to $\approx 1\%$. His unit, the astronomical unit (AU), was of unknown size. The technique was geometry:

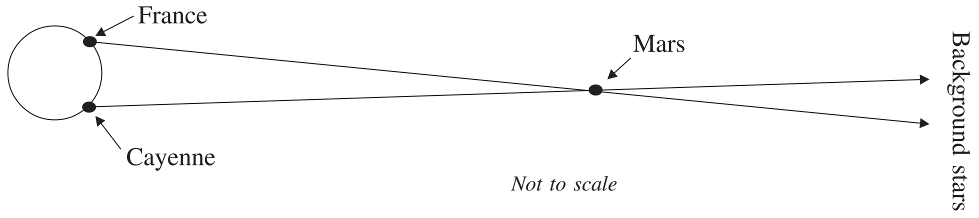


If one assumes circular orbits and constant velocities along orbits (can check this observationally), then the dates of opposition/quadrature/greatest elongation/conjunction give the *relative* geometry.

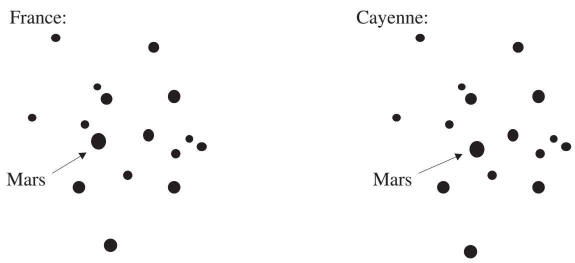
1.2.2 Parallax of Mars, transits of Venus determine scale

Putting a *scale* on things requires that any one distance be known both in AU and in km.

1671: French expedition to Cayenne (French Guiana, home of hot peppers) measured parallax of Mars at opposition:



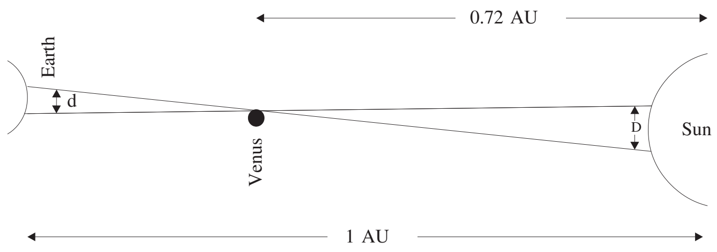
Of course,what is actually *seen* is:



They got the answer wrong (or right!) to $\approx 10\%$.

[Technology aside: Micrometer sights were first used in the 1670's.]

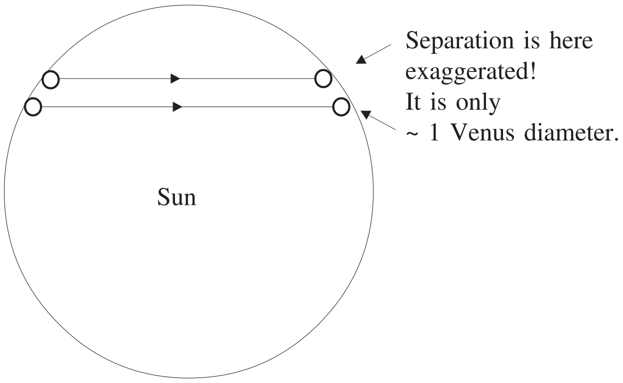
Halley, in 1716 (age 60) pointed out that the "transit of Venus" in 1761 and 1769 could be used. He knew he would be dead by then and told all *young* astronomers about it. (These transits are *quite* infrequent: next ones were 1874, 1882, June 7, 2004, June 5, 2012.)



Note there is a geometrical magnification factor that helps:

$$\frac{D}{d} = \frac{0.72}{0.28} \, .$$

So from different *latitudes* on $\oplus$ one sees different tracks.



How to measure small separation from opposite sides of globe? Not by subtracting measurements of height from "top" of sun — too imprecise. Rather, take the *average* height to get the geometry, and use the difference of transit *ingress/egress times or durations* to infer the small differences.

Order of magnitude (ignoring magnification factors, geometry, etc.):

$\oplus$ and $♀$ diameters $\approx 12000\,\mathrm{km} \sim 10^4\,\mathrm{km}$

$\odot$ diameter $\approx 1.5 \times 10^6\,\mathrm{km} \sim 10^6\,\mathrm{km}$

$♀ - \oplus$ velocity $\sim 10\,\mathrm{km/\,s}$

$\Rightarrow 10^3\,\mathrm{s}$ to move $♀$ diameter, $10^5\,\mathrm{s} \sim 1$ day to move across $\odot$

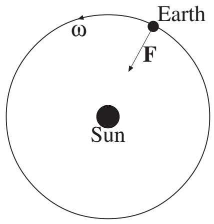
In 1761 and 1769 various discrepant results $\pm 10\%$ were obtained. Not until 1835 was an accurate value obtained (by Encke) *from these same measurements*: Gauss had, in the meanwhile, discovered *least squares fitting* for combining observations!

A modern value is

$$1\,\mathrm{AU} = 149{,}597{,}870 \pm 1\,\mathrm{km}\ .$$

1.2.3 Newton's Law of Gravitation gives mass of Sun

Given the AU, we can use Newton's Law of Gravitation to get the mass of the Sun. This is probably the first example of true astro*physics*:



$$\frac{GM_\odot m_\oplus}{R^2} = F = m_\oplus \omega^2 R$$
"gravity = centripetal acceleration"

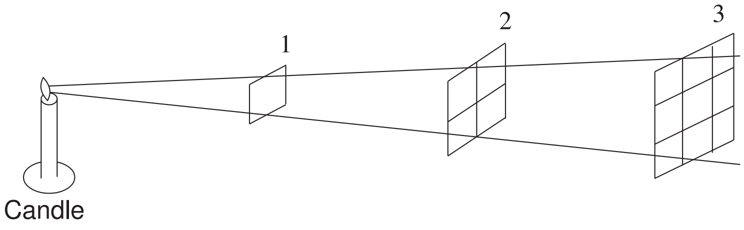
So:

$$\begin{aligned} M_\odot &= \frac{\omega^2 R^3}{G} = \frac{\left(\frac{2\pi}{1\,\mathrm{yr}}\right)^2 \left(\frac{1\,\mathrm{yr}}{3.16 \times 10^7\,\mathrm{s}}\right)^2 (1.50 \times 10^{13}\,\mathrm{cm})^3}{6.67 \times 10^{-8}\,\mathrm{cm}^3\,\mathrm{g}^{-1}\,\mathrm{s}^{-2}} \\ &= 2.00 \times 10^{33}\,\mathrm{g} \end{aligned}$$

(a modern value is 1.989×10^{33} g).

1.2.4 Compare Sun to candle to get its "candlepower"

What is the "solar luminosity" $L_\odot$ (power or energy per time emitted by $\odot$)? Use inverse square law for radiant flux, a form of conservation energy:



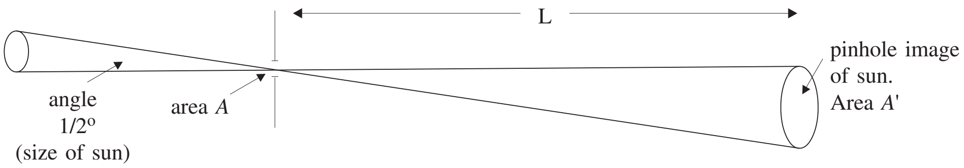
How to compare $\odot$ to a candle? Not easy before electrical measurements!

In modern units, solar illuminance is 127000 lux.

$$
\begin{aligned}
1 \text{ lumen} &= \text{light emitted by } \frac{1}{60\pi}\,\text{cm}^2 \text{ blackbody} \\
& \text{ at the melting point of platinum, } 2044\,\text{K} \\
1 \text{ lux} &= 1 \text{ lumen/m}^2 \approx 1 \text{ candle at } 1\,\text{m}
\end{aligned}
$$

A bright ($m_V = 0$) star is 2.5×10^{-6} lux.

A good VCR camera (with a charge-coupled device (CCD)) works down to 5 lux. Use a pinhole to get $\odot$ into candle-comparison range:



All light incident on area A appears spread out over an area

$$
\begin{aligned}
A' = \frac{\pi D^2}{4} &= \frac{\pi}{4} \cdot \left(L \cdot \frac{1^\circ}{2} \cdot \frac{1 \text{ rad}}{57.3^\circ} \right)^2 \\
&= L^2 \times 6.0 \times 10^{-5}\ .
\end{aligned}
$$

So brightness diminished by a factor (> 1)

$$
\frac{A'}{A} = \frac{L^2}{A} \times 6.0 \times 10^{-5}\ .
$$

Taking $L = 20\,\text{m} = 2 \times 10^3\,\text{cm}$, $A = (.1\,\text{cm})^2 = 10^{-2}\,\text{cm}^2$. This gives $A'/A = 24000$, which gets sun down to ~ 5 candles at $1\,\text{m}$ or 1 candle at $45\,\text{cm}$.

So, by this and similar techniques, around time of Huygens (1650) people knew the "candlepower" of the Sun:

$$
\begin{aligned}
127000 \text{ candles} \times \left(\frac{1\,\text{AU}}{1\,\text{m}} \right)^2 &= 127000 \times \left(\frac{1.5 \times 10^{11}\,\text{m}}{1\,\text{m}} \right)^2 \text{ candles} \\
&= 2.8 \times 10^{27} \text{ candles.}
\end{aligned}
$$

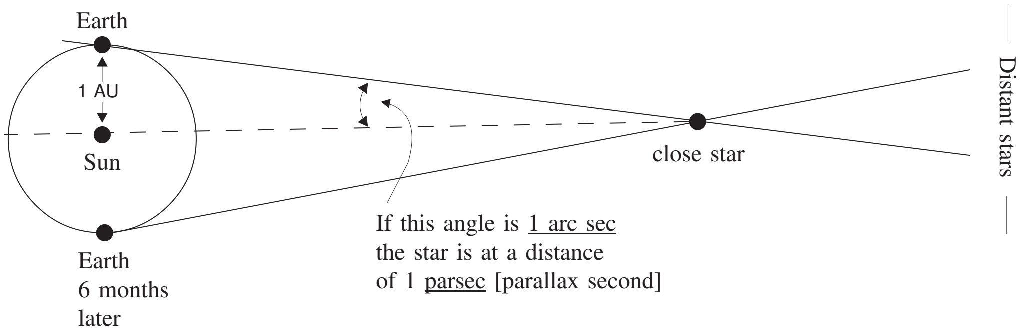
Huygens also thought that Sirius (modern $m_V = -1.45$) was as bright as a candle at 80 m. So, *if* it was same intrinsic brightness as Sun:

$$\frac{D_{\text{Sirius}}}{D_{\text{Sun}}} = \sqrt{\frac{127000}{(1/80)^2}} \approx 29000\,\text{AU}$$
$$\approx \frac{1}{2}\text{ light year.}$$

We now know that the actual distance to Sirius is $\approx$ 550000 AU (8.8 l.y.). (It is much brighter intrinsically than the sun, and Huygen's calibration of it in candles was also not accurate.)

1.2.5 Stellar distances from Parallax across Earth's orbit

The first *accurate* stellar distances came from parallax across the Earth's orbit:



Since

$$1\,\text{arcsec} = 1\,\text{arcsec} \times \left(\frac{1^\circ}{3600\,\text{arcsec}}\right)\left(\frac{\pi\text{ rad}}{180^\circ}\right)$$
$$= \frac{1}{206265}\text{ rad.}$$

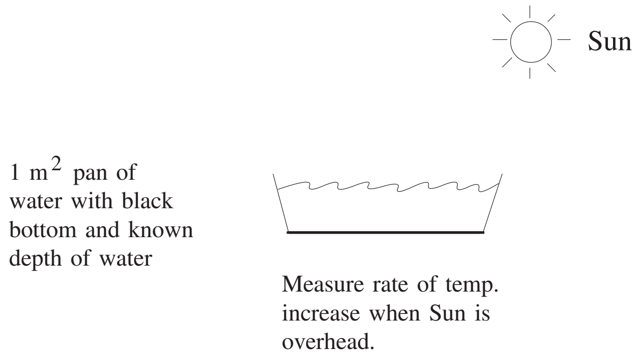
So 1 pc $\equiv$ 206265 AU (= 3.26 ly).

With modest astrometric telescopes (and lots of effort) direct parallaxes are possible out to 10–50 pc (0.1 to 0.02 arcsec). Beyond that, indirect methods must be used.

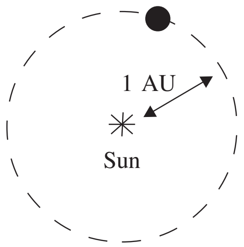
First parallaxes date from 1839–1840: Bessel, von Struve. Technology note: both used lenses made by Fraunhofer (Bavaria).

1.2.6 Luminosities in modern units (watts)

We never did get $L_\odot$ in watts (or erg/s) because we got sidetracked into "candles." Historically this of course had no meaning until Joule discovered the "mechanical equivalent of heat" (calories per joule) in 1847; before that we could only discuss $L_\odot$ in calories/s:



Correcting for *absorption in atmosphere*[1], the answer "the solar constant" is about 1400 W/m^2. So:



$$
\begin{aligned}
\frac{L_\odot}{4\pi(1\,\mathrm{AU})^2} &= 1400\,W/\mathrm{m}^2 \\
\Rightarrow L_\odot &= 4\pi \times 1400 \times (149 \times 10^9\,\mathrm{m})^2 \\
&= 3.9 \times 10^{26}\mathrm{W} = 3.9 \times 10^{33}\,\mathrm{erg/s}.
\end{aligned}
$$

[1] How? Try different times of day and measure secant effect, e.g.