ASTR 221 – Stars & Planets

Fall 2021

MW 12:45-2:00 Sears Library 552

Bill Janesh

ASTR 221 — Stars and Planets

Time: Mondays & Wednesdays, 12:45 pm - 2:00 pm
Place: Sears Library 552 (the "Astronomy Classroom")
Instructor: Bill Janesh bfj2@case.edu **TA:** Ray Garner crg56@case.edu
Course Webpage: ***http://astroweb.case.edu/bjanesh/astr221/ & Canvas for announcements and grades***
Required Text: ***Foundations of Astrophysics*, by Ryden and Peterson (ISBN 978-1-108-83195-6)**
Other Useful Books: *Astronomy: A Physical Perspective, 2e,* by Kutner
Introduction to Modern Astrophysics, 2e, by Carroll and Ostlie

Grades:

Homework:	**45%**	*We will use the CWRU Standard Grading Scheme*
Midterm:	**25%**	*(A≥90% | B≥80% | C≥70% | D≥60% | etc.)*
Final Exam:	**30%**	

Course Description: Stellar structure and energy production. Formation and evolution of stars. Supernovae, neutron stars, and black holes. Star clusters. Planetary systems and the detection of extrasolar planets. The application of physical laws to the study of the universe.

Disability Accommodations: In accordance with federal law, if you have a documented disability, you may be eligible to request accommodations from Disability Resources. In order to be considered for accommodations you must first register with the Disability Resources office. Please contact their office at 216.368.5230 to register or get more information on how to begin the process. Keep in mind that accommodations are not retroactive.

Homework: There will be a total of **6** homework assignments. Collaborative discussion is permitted and encouraged, but **each person must turn in their own solutions with unique writeup/analysis**. Collaborative means talking with each other about approaches, techniques, etc., and *not* swapping final solutions to copy! **Submissions will be accepted on paper or in PDF format via Canvas.** Write-ups should be typed or *neatly* handwritten. For PDF submissions, scan your handwritten work properly (see homework tips page for suggestions) and please make an effort to merge all parts into a single file for submission. **Homework will generally be due in class** but see each assignment for specifics.

Exams: There will be one midterm and one final exam. **You are allowed one sheet of letter/A4-sized paper with notes on both sides,** but exam questions will ask you to synthesize information from what you know, not just work a problem or cite facts. You **may not** work collaboratively with your classmates, and I'll only answer clarifying or format questions. The final exam is scheduled for 12/15 from 12-3pm, please register any time conflicts with Undergraduate Studies. *Academic integrity violations during an exam will result in, at minimum, the failure of the exam.*

Attendance/Late Policy: *Attendance:* you are **encouraged, but not required, to attend lectures**. I will be recording class audio, which will be posted on the course webpage along with slides and notes. *Late work:* **You get one free no excuse late homework (up to one week). All other late work loses 20% per day.** If you have an emergency or otherwise legitimate reason out of your control for missing a homework due date (illness, technology issues, etc.), please document this with your Navigator and me ASAP. We'll then work out an alternate due date without penalty.

Computing: Some HW assignments will **require you to write and run code in Python** to solve astronomical problems. Don't worry — we'll spend at least one class getting more familiar with Python before I ask you to use it, but **ask for help if you need it**. Typed reports can easily be created using a Jupyter notebook, showing formatted text alongside code and math. *If you would like access to departmental computing resources, or have questions or concerns about this aspect of the course, please let me know as soon as possible.*

Office Hours: Mondays and Wednesdays the hour after class ends, and a 90 minute block on Thursday decided by class popular vote, or just drop in! Some questions can probably be answered via email; I will do my best to respond as soon as possible during normal business hours. If you have a question in person, please come prepared — for homework questions, you must attempt the problem on your own first! I will ask you to show me what you've tried before I answer questions. If you're not sure where to start, see the homework tips page.

Ray - Tues: 10-11 Fri 2-3

	Date	General Topic	*Ryden & Peterson* Readings	Due
Week 1	*Aug 23*	Introductions; Orbits and Kepler's Laws	2.3, 2.5, 3.1	
	Aug 25	Orbits and Kepler's Laws; Gravity; Tides	3.1-3.4, 4.2, 4.3	
Week 2	*Aug 30*	The Sky; Constellations	1.3-1.6, 2.1, 2.2	
	Sept 1	Celestial Sphere; Coordinate Systems	1.1, 1.2	
Week 3	*Sept 6*	Labor Day (no class)		
	Sept 8	Light; Radiation; Blackbodies; Spectra	5.1-5.7	HW1
Week 4	*Sept 13*	Astronomical Techniques; Telescopes	6.1-6.7	
	Sept 15	Python Introduction	bring a computer!	
Week 5	*Sept 20*	The Sun; Hydrostatic Equilibrium	7.1-7.3, 14.1	
	Sept 22	Distances, Magnitudes, Colors	13.1-13.2	HW2
Week 6	*Sept 27*	Spectral Types; The H-R Diagram	13.3-13.6, 14.2-14.4	
	Sept 29	Velocities; Binary Stars; Stellar Masses	13.5	
Week 7	*Oct 4*	Nuclear Fusion; Energy Transport in Stars	15.1-15.4	
	Oct 6	Low Mass Stellar Evolution	17.2	HW3
Week 8	*Oct 11*	Review!		
	Oct 13	Midterm Exam	don't forget your notes sheet!	
Week 9	*Oct 18*	Fall Break (no class)		
	Oct 20	High Mass Stellar Evolution; Supernovae	17.3	
Week 10	*Oct 25*	White Dwarfs, Neutron Stars, Black Holes	18.1-18.4	
	Oct 27	Star Clusters	14.2-14.4, 17.2, 17.3	HW4
Week 11	*Nov 1*	Interstellar Medium; Star Formation	16.1-16.3, 17.1	
	Nov 3	Star Formation	17.1	
Week 12	*Nov 8*	Solar System Formation	8.1-8.3, 12.2	
	Nov 10	The Earth and Moon	9.1-9.5	HW5
Week 13	*Nov 15*	Rocky Planets; Interior Processes	10.1	
	Nov 17	Moons; Comets; Asteroids; Tiny Things	11.1-11.4	
Week 14	*Nov 22*	Atmospheres; Gas Giants	10.2-10.3, 9.2	
	Nov 24	Gas Giants	10.2-10.3	
Week 15	*Nov 29*	Exoplanets	12.3-12.4	
	Dec 1	Exoplanets	12.3-12.4	HW6
	Dec 15	Final Exam 12-3pm		don't forget your notes sheet!

8/23 Orbits & Kepler's Laws

How did astronomy become a thing?

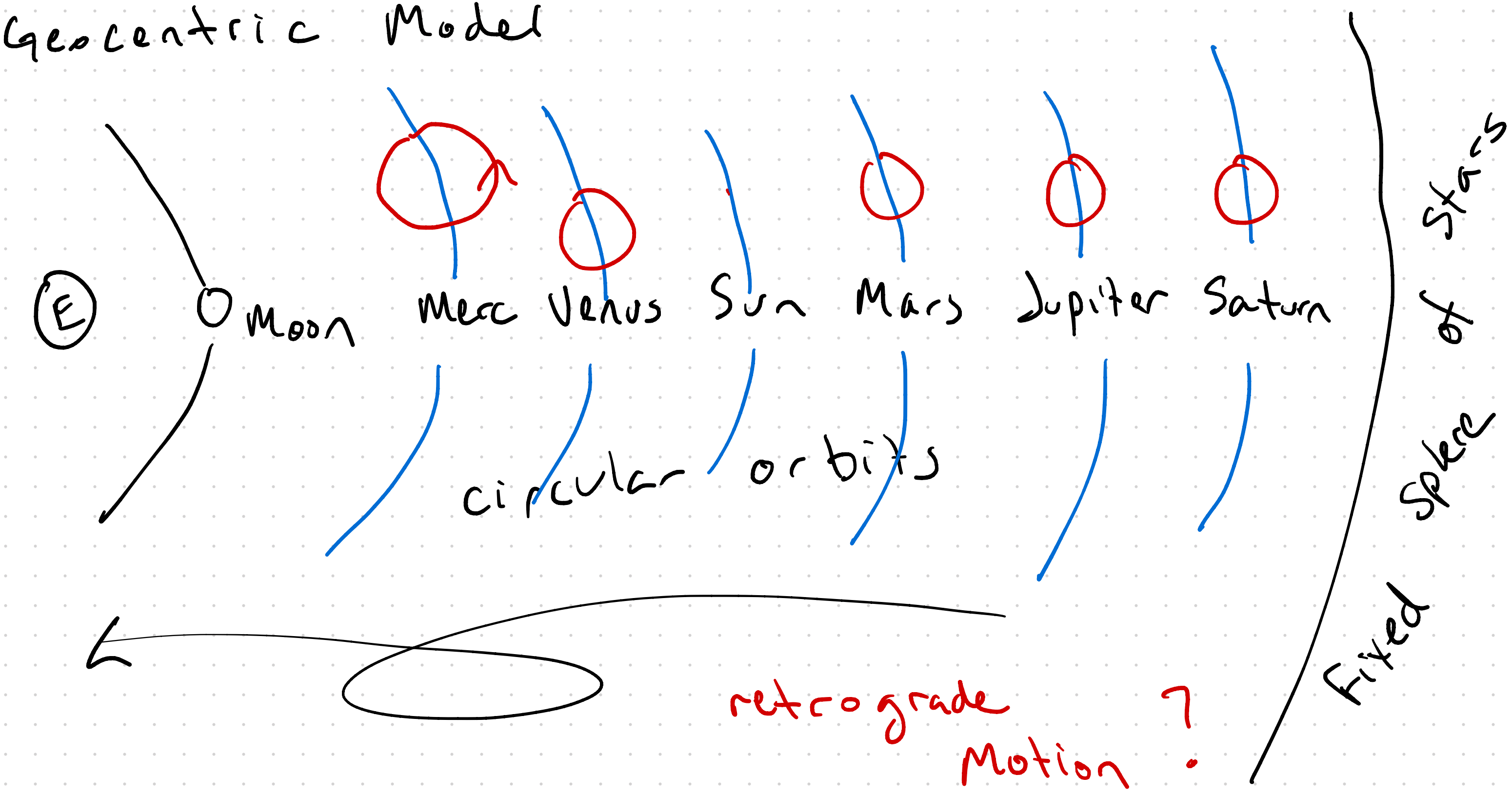
Navigation, time, seasons, religion

what's that stuff in the sky?

gravity.

why am I here?

Geocentric Model



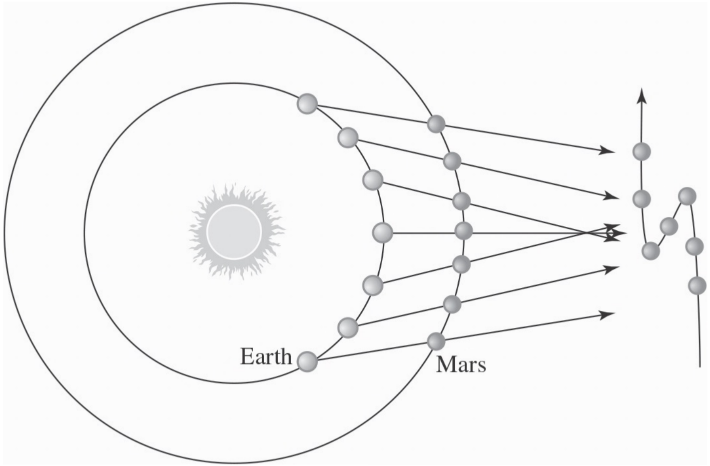
Simplify?

Heliocentric Model

Moon

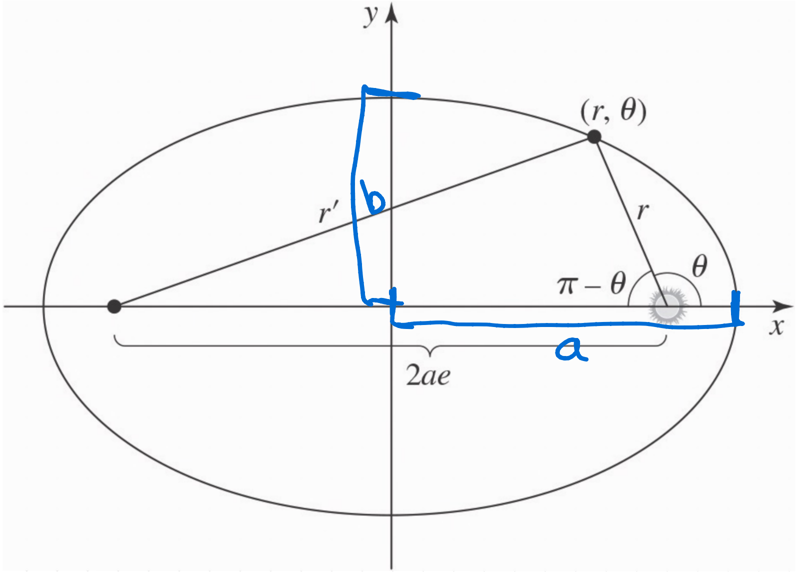
Sun Mercury Venus Earth Mars Jupiter Saturn

Fixed sphere of stars



Kepler's 1st Law

planets orbit in ellipses, with the Sun at one focus of the ellipse



a	semi-major axis
b	semi-minor axis
e	ellipticity / eccentricity

$$= \sqrt{1-\left(\frac{b}{a}\right)^2}$$

$e = 0$ circle

$e = 1$ straight line

periapse (closest approach to star)

perihelion

perigee

periastron

perigalacticon

$$r_p = a(1-e)$$

apo apse (furthest)

aphelion

apogee

apo astron

$$r_a = a(1+e)$$

$$e_{Earth} = 0.017$$

Astronomical Unit (AU)

"mean distance between Earth & Sun"

150 million km 93 million miles

semi-major axis of Earth's orbit

$a = 1.0$ AU

	a	e	P
Mercury	0.39 AU	0.205	0.24 years
Venus	0.72	0.007	0.62
Earth	1.0	0.017	1.0
Mars	1.52	0.093	1.88
Jupiter	5.20	0.048	11.86
Saturn	9.54	0.054	29.45
Uranus	19.19	0.047	84.02
Neptune	30.07	0.009	164.8
Pluto	39.45	0.250	247.9
Comets	varies	0.75-0.995	varies

Kepler's 3rd Law

"for all planets, the orbital period squared divided by the semi-major axis cubed is constant."

$$p^2 \propto k a^3$$

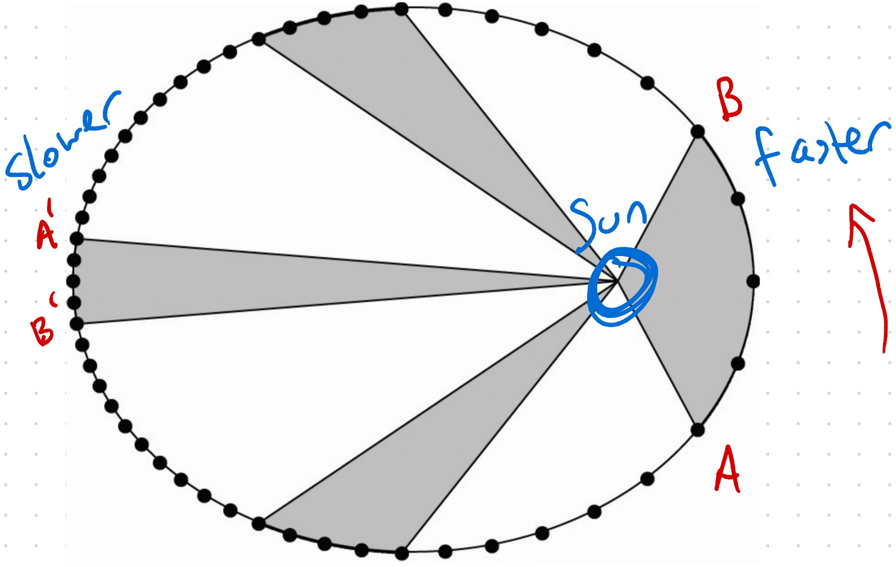
years AU

Kepler's 2nd Law

The Law of Equal areas

"The line connecting a planet & the Sun sweeps out equal areas in equal amounts of time."

planets move <u>faster</u> in their orbits when they are <u>closer</u> to the Sun

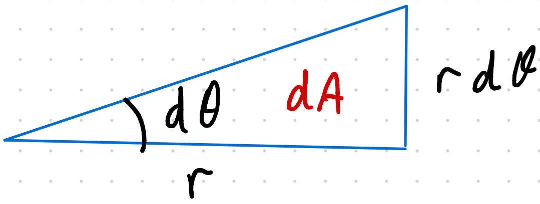


Kepler's 1st Law Revisited

The Earth does not orbit the Sun. (?)

Each object moves on an ellipse w/ COM at one focus of the ellipse.

Kepler's 2nd Law Revisited



$$dA = \frac{1}{2} r (r\,d\theta)$$

$$\frac{dA}{dt} = \frac{1}{2} r \left(r \frac{d\theta}{dt}\right)$$

$$= \frac{1}{2} r v_\theta$$

$$\vec{L} = m(\vec{r} \times \vec{v})$$

$$\Rightarrow \quad L = m r v_\theta \qquad \frac{L}{m} = r v_\theta$$

$$\underbrace{\frac{dA}{dt}}_{\text{constant}} = \frac{1}{2} \frac{L}{m}$$

Kepler's 3rd Law Revisited

$$G = 6.67 \times 10^{-11} \frac{m^3}{kg\, s^2}$$

$$F_g = \frac{GMm}{r^2} \qquad F_{cent} = \frac{mv^2}{r_1}$$

$$\frac{GMm}{r^2} = \frac{mv^2}{r_1} \qquad v = \frac{2\pi r}{P} \qquad r_1 = \frac{M}{m+M} r$$

$$\frac{GM\cancel{m}}{r^2} = \frac{\cancel{m}\, 4\pi^2 r_1}{P^2}$$

$$\frac{G\cancel{M}}{r^2} = \frac{4\pi^2}{P^2} \frac{\cancel{M}}{m+M} r \qquad G = 4\pi^2 \frac{\mathrm{AU}^3}{M_\odot\, \mathrm{yr}^2}$$

$$P^2 = \frac{4\pi^2}{G(m+M)} r^3 = a^3$$

Does an orbit have to be an ellipse or a circle?

Orbital Classification

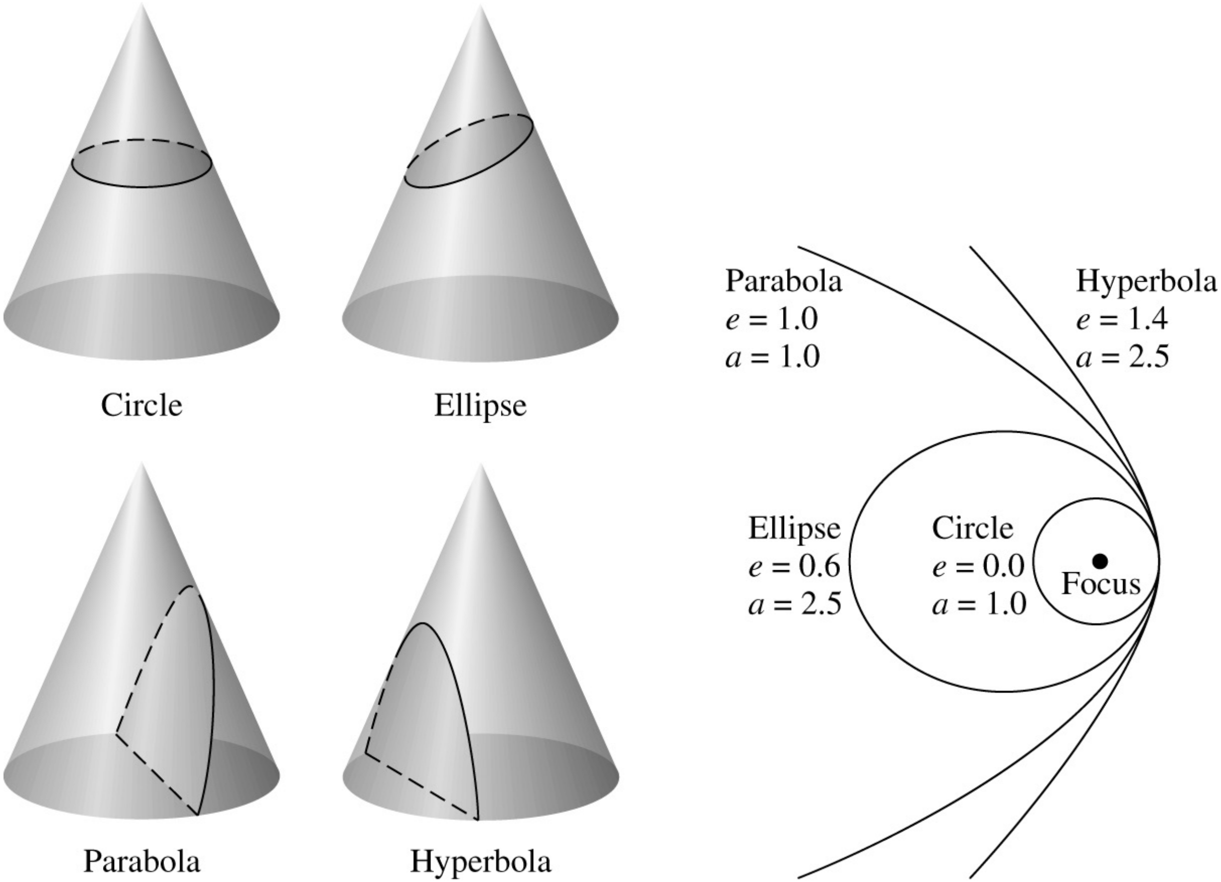
closed	v	open
$E_{tot} < 0$		$E_{tot} > 0$
kinetic < potential		kinetic > potential
bound		unbound
circular, elliptical		hyperbola

"critical"

$E_{tot} = 0$

kinetic = potential

parabolic


Circle
Ellipse
Parabola
Hyperbola
Parabola
e = 1.0
a = 1.0
Hyperbola
e = 1.4
a = 2.5
Ellipse
e = 0.6
a = 2.5
Circle
e = 0.0
a = 1.0
Focus

(a) (b)

Gravitational Potential Energy

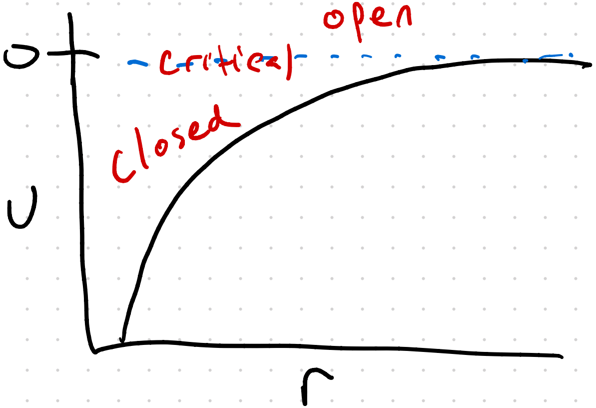
push it away from the sun

$$\Delta U = -\int_{\vec{r}_i}^{\vec{r}_f} \vec{F}\, d\vec{r} = -\int_{r_i}^{r_f} G\frac{Mm}{r^2}\, dr$$

$$U_f - U_i = -GMm\left(\frac{1}{r_f} - \frac{1}{r_i}\right)$$

$$U(\infty) \equiv 0$$

$$U = -\frac{GMm}{r}$$



$$K = \frac{1}{2}\underset{\substack{\uparrow \\ \text{planet}}}{m} v^2$$

$$K + U = \text{constant}$$

$$E_{tot} = \frac{1}{2} m v^2 - \frac{GMm}{r}$$

$$0 = \frac{1}{2} m v_{esc}^2 - \frac{GMm}{r}$$

$$v_{esc} = \left(\frac{2GM}{r}\right)^{1/2}$$

$$v_c = \frac{2\pi a}{P} \qquad p^2 = \frac{4\pi^2}{GM} a^3$$

$$v_c^2 = \frac{4\pi^2 a^2}{p^2}$$

$$v_c^2 = \frac{4\pi a^2}{4\pi a^3} GM \Rightarrow v_c^2 = \frac{GM}{a}$$

$$E_{tot} = \frac{1}{2} m v^2 - \frac{GMm}{a}$$

$$= \frac{1}{2} m \frac{GM}{a} - \frac{GMm}{a} \qquad K = \frac{1}{2} U$$

$$= -\frac{GMm}{2a}$$

Generalized orbital Speed

$$\frac{1}{2}mv^2 - \frac{GMm}{r} = -\frac{GMm}{2a}$$

$$\frac{1}{2}\cancel{m}v^2 = \frac{GM\cancel{m}}{r} - \frac{GM\cancel{m}}{2a}$$

$$v^2 = GM\left(\frac{2}{r} - \frac{1}{a}\right)$$

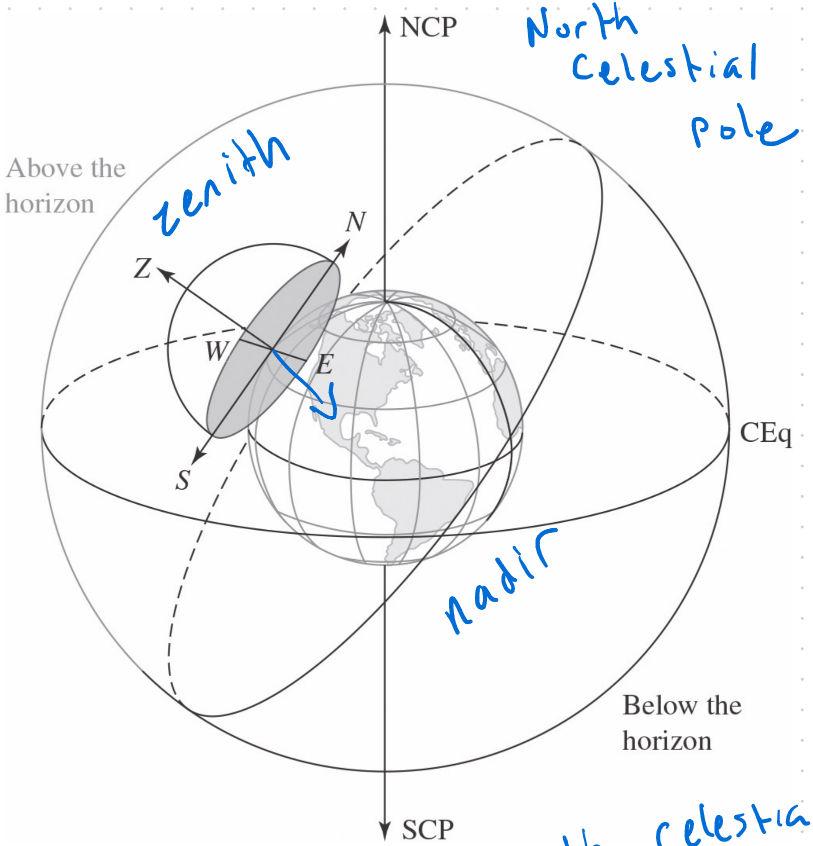
perihelion $v_p^2 = \frac{GM}{a}\left(\frac{1+e}{1-e}\right)$

aphelion $v_a^2 = \frac{GM}{a}\left(\frac{1-e}{1+e}\right)$

The Sky

+6

+2 campus



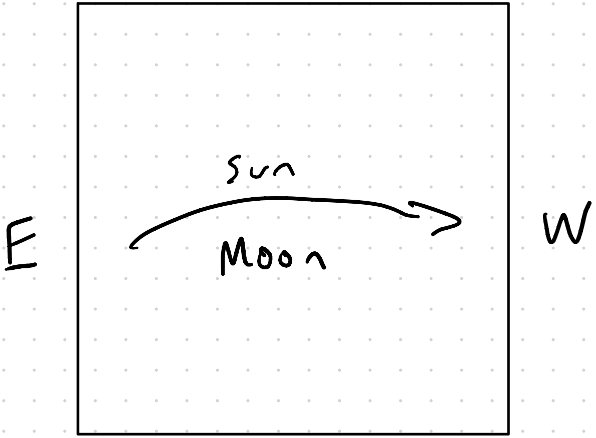
North celestial pole

zenith

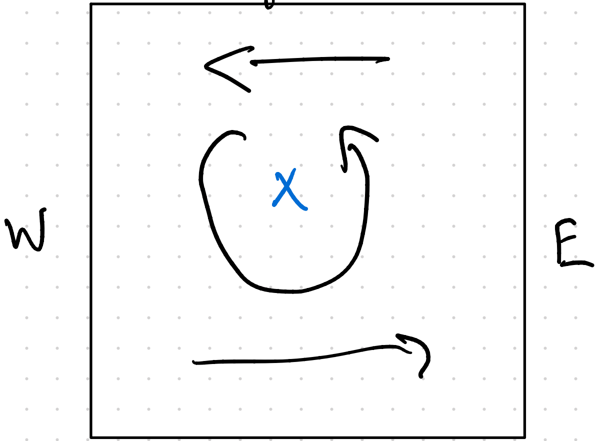
celestial equator

nadir

south celestial pole



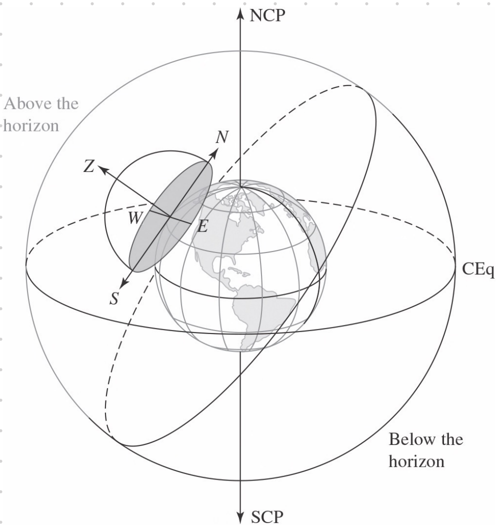
looking South

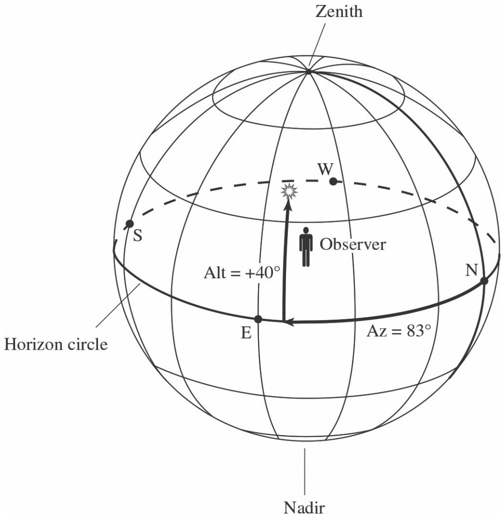


looking North

Circumpolar Stars

$$\text{Latitude} > 90^\circ - \underset{42}{\ell^\circ}$$





Altitude - Azimuth

"Horizon" System

latitude - longitude

Equatorial Coordinates

$(\overset{\circ}{\theta}, \overset{\circ}{\varphi}, \overset{\circ}{r})$

- aligned to Earth's system
- $\theta, \varphi = 0, 0$ → where the ecliptic @ equator cross on the vernal equinox ♈
- declination (latitude) δ degrees

RA - right ascension (longitude) α hours ???

1 hour = 15 degrees

hours   degrees

minutes != arcminutes 1/60 degree

seconds != arc seconds 1/60 arcminute

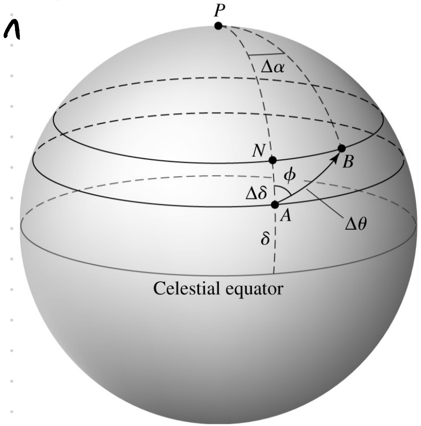
$(5^h\ 55^m\ 12^s,\ 12^\circ\ 15'\ 25'')$

Angular separation $(\Delta\theta)$ degrees, arcmin

$$\Delta\alpha = \Delta\theta \frac{\sin\phi}{\cos\delta}$$

$$\Delta\delta = \Delta\theta \cos\phi$$

$$(\Delta\theta)^2 = (\Delta\alpha \cos\delta)^2 + (\Delta\delta)^2$$



Sidereal Time

the amount of "clock time" since the vernal equinox crossed the meridian

the RA coordinate of a star crossing the meridian at a given point in time

meridian = the line that passes through North, zenith, South perpendicular to horizon

Betelgeuse = 5h 55m

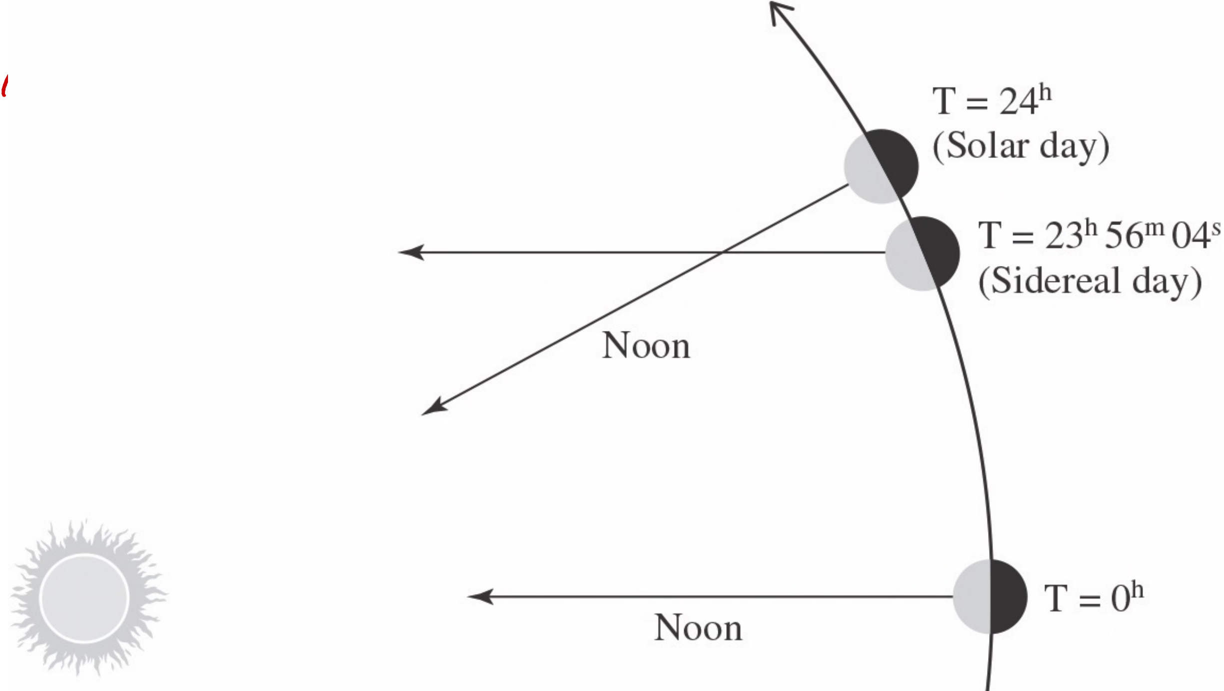
Sidereal Day

length of time between successive crossings of the vernal equinox over the

23h

Solar Day

length of time between successive crossings of the Sun over the meridian



Light

What is light?

"Sometimes" it's a wave

"sometimes" it's a particle -> photon (no mass)

Fast! 3×10^8 m/s

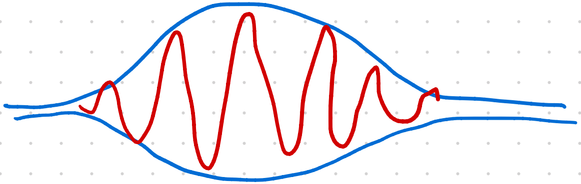
3×10^5 km/s

Energy

some behavior can be described by a wave ~

" " " " " particle how?

wave	particle
wavelength	photoelectric effect
double-slit experiment	travel over long distances
Doppler effect	momentum $E = pc$
antenna	gravity



Electromagnetic Spectrum

$$\lambda \cdot f = c$$

wavelength	frequency	speed of light
length	1/time	length/time

EM bands

Gamma Rays	high f	$\lambda < 1$ nm
X-rays		$1 \text{ nm} < \lambda < 10$ nm
UV		$10 \text{ nm} < \lambda < 400$ nm
visible (optical)		$400 \text{ nm} < \lambda < 700$ nm
IR		$700 \text{ nm} < \lambda < 1$ mm
Microwave		$1 \text{ mm} < \lambda < 10$ cm
Radio	low f	$10 \text{ cm} > \lambda$

Ångstrom = 0.1 nm

$\text{Å} = 1 \times 10^{-10}$ m

why is light useful?

elemental composition
direction of motion
presence of light-emitting objects
temperature
density

Kirchoff's Laws

1. a hot, dense gas or solid object emits a
continuous spectrum "all wavelengths, unbroken"

2. hot, diffuse gas produces bright spectral lines
"emission spectrum"

3. a cool, diffuse gas in front of a continuous spectrum
produces dark spectral lines → "absorption spectrum"

HW 2 now due 9/27 @ 2pm

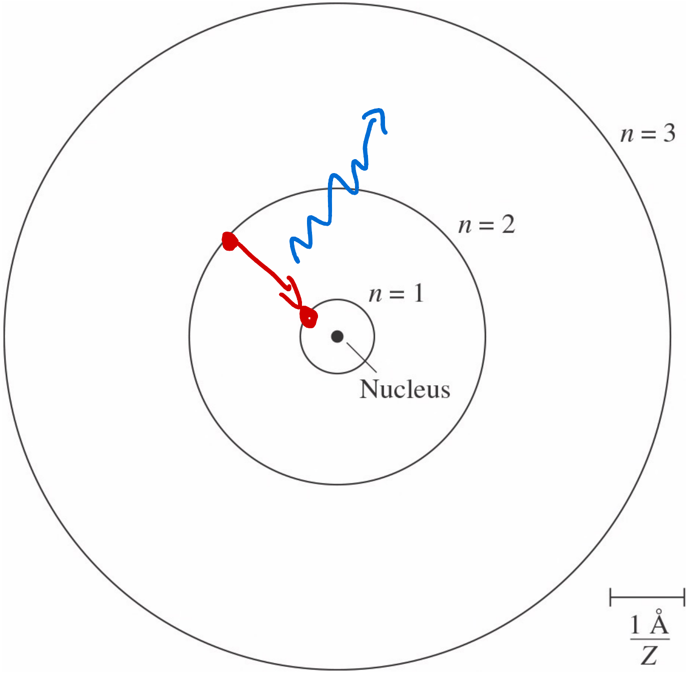
Python Intro Wednesday 9/15

hydrogen

$$E_n = \frac{-13.6 \text{ eV}}{n^2}$$

$$\Delta E = E_f - E_i$$

$$= E_1 - E_2$$



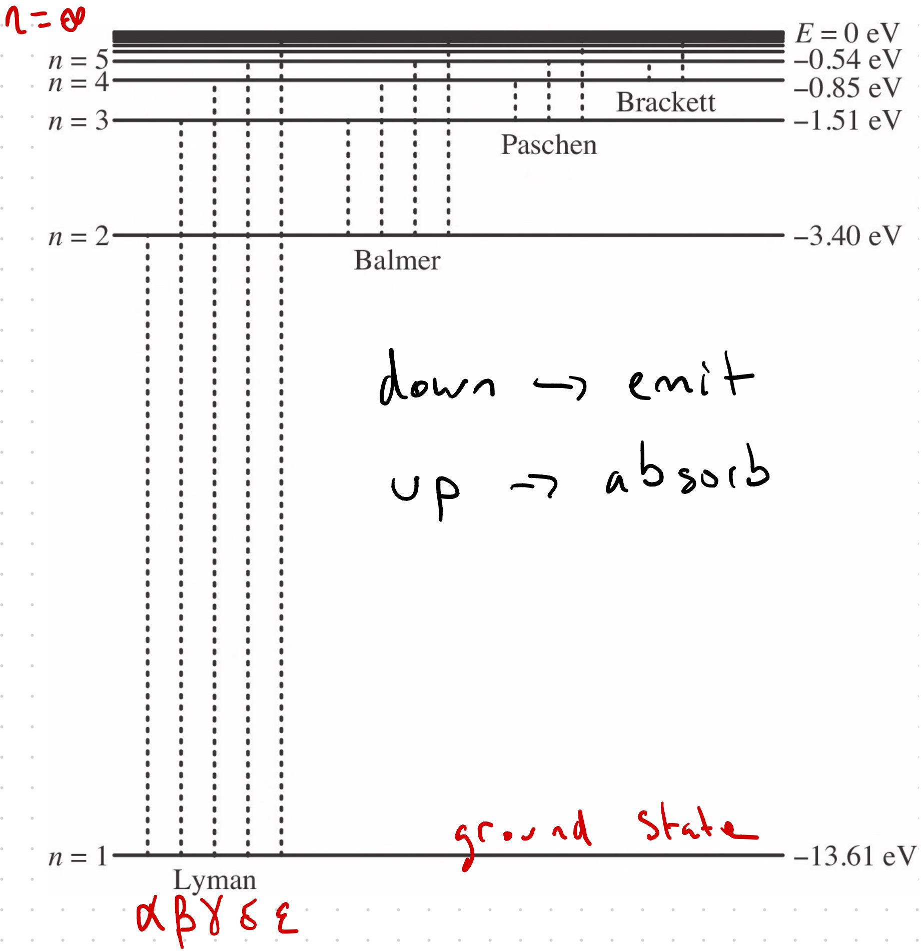
$$E_\gamma = hf$$

h = planck constant

6.626×10^{-34} J · Hz

$$E_\gamma = \frac{hc}{\lambda}$$

$$\boxed{\Delta E_{if} = \frac{hc}{\lambda}}$$



down → emit

up → absorb

Balmer Series

n = 2 ⟷ 3 Hα 656.3nm

n = 2 ⟷ 4 Hβ 486.1nm

n = 2 ⟷ 5 Hγ 434.0nm

n = 2 ⟷ 6 Hδ 410.2nm

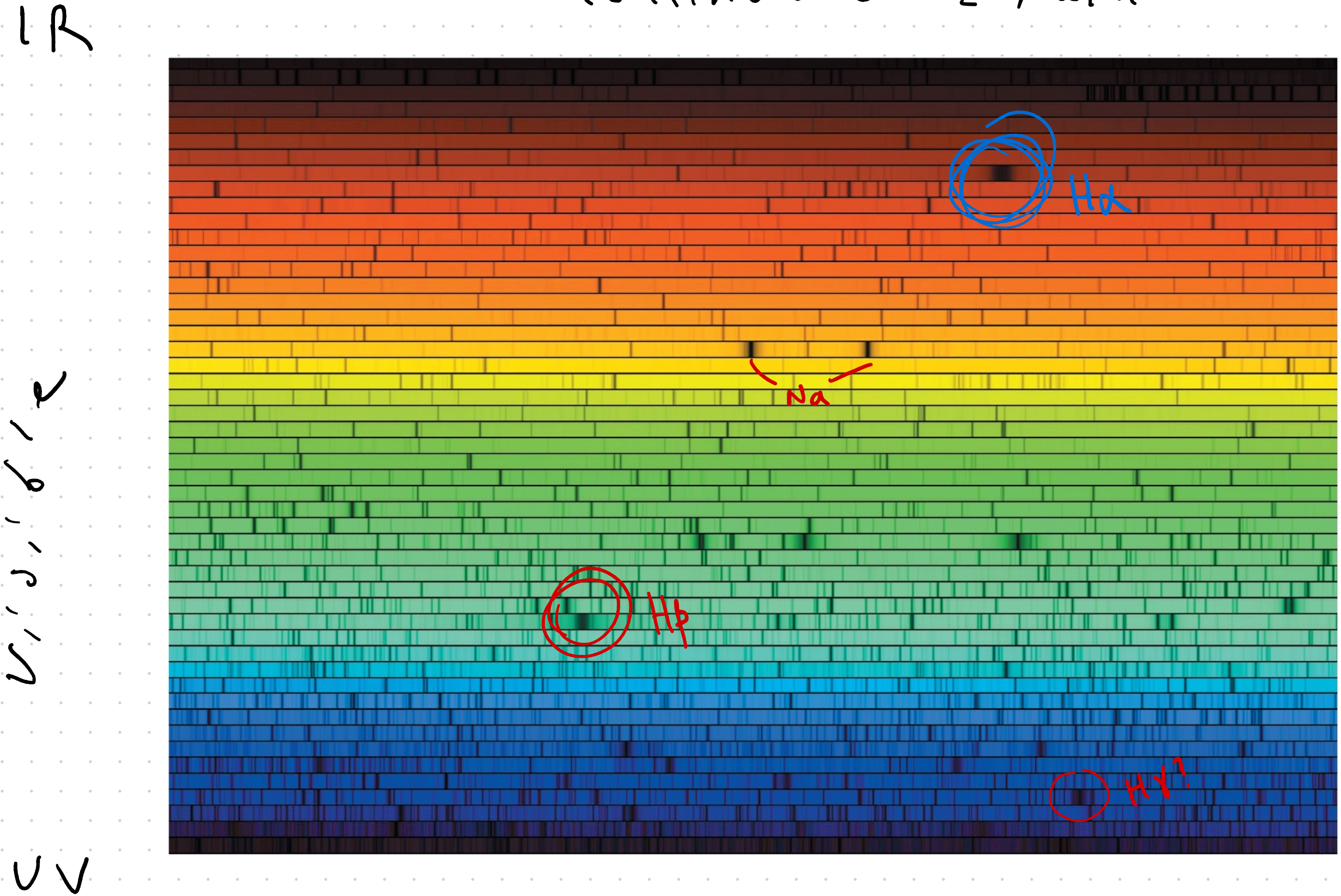
ionization

collisional excitation

kinetic energy

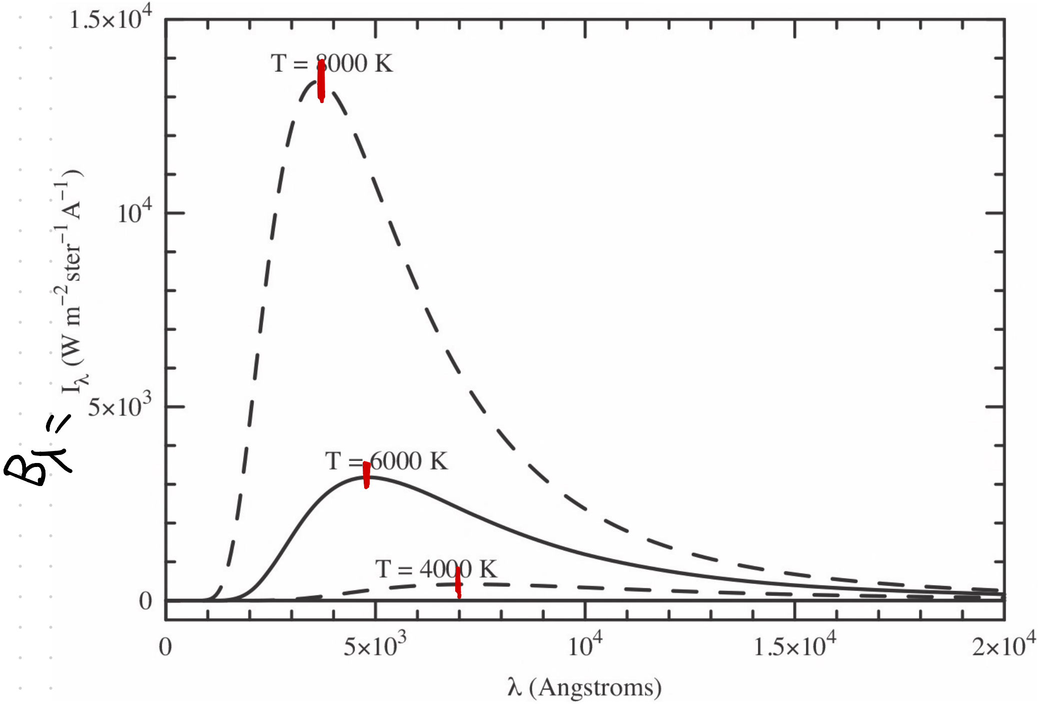
$K = \frac{1}{2}mv^2$

continuous = rainbow



"ideal emitter" - absorbs all the light that is incident upon it, then reradiates the same amount of energy in a characteristic spectrum

"blackbody"



Wien's Law

$$\lambda_{max} = \frac{0.0029 \text{ m}\cdot\text{K}}{T}$$

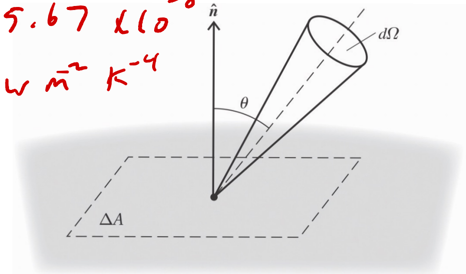
Luminosity

$$L = A\sigma T^4$$

σ = Stefan-Boltzmann constant

5.67×10^{-8}

W m^{-2} K^{-4}



Planck Equation

$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{e^{(hc/\lambda kT)} - 1}$$

↗ Intensity

h = Planck

k = Boltzmann

c = speed of light

$$L_\lambda \, d\lambda = B_\lambda(T) \, \underset{\text{Å}}{d\lambda} \, \underset{m^2}{dA} \, \cos\theta \, \underset{sr}{d\Omega}$$

Telescopes

what is a telescope?

why is it useful (for astronomy)?

lenses & Mirrors

Magnification / Resolution

Different EM bands

see to further distances

Light Gathering Power

bigger is better

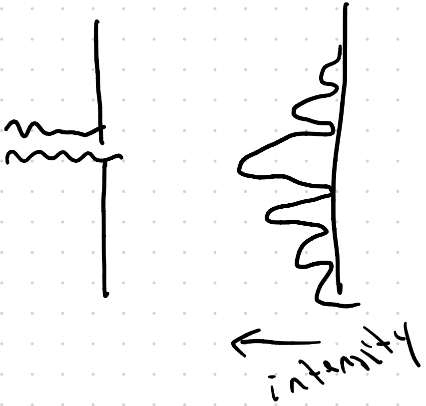
$$LGP \propto d^2 = Are$$

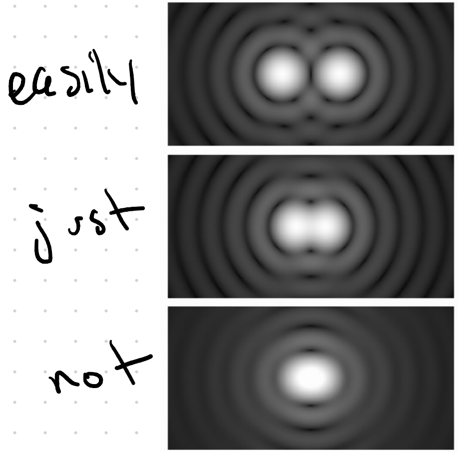
Resolution

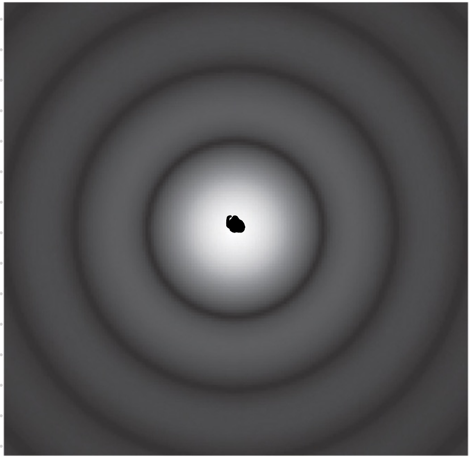
"see more detail"

smaller is better

Limited by diffraction of light







Airy Disk

Rayleigh Criterion

"minimum resolvable angular distance between two objects"

two objects are just resolved when the central maximum overlaps the 1st minimum of the other

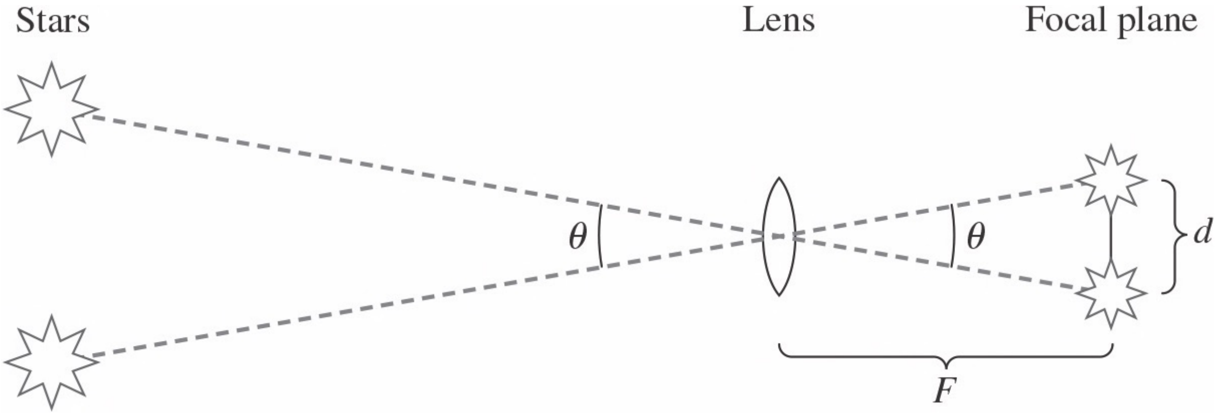
radians

$$\theta_{min} = \frac{1.22\lambda}{D}$$

wavelength of light

aperture diameter

Simplest possible design - a single lens



angular separation θ

≈ size of image

Focal length

how far away from lens is image in focus

$$\tan\theta = \frac{d}{F}$$

$$\tan\theta \approx \theta$$

radians $$\theta = \frac{d}{F}$$

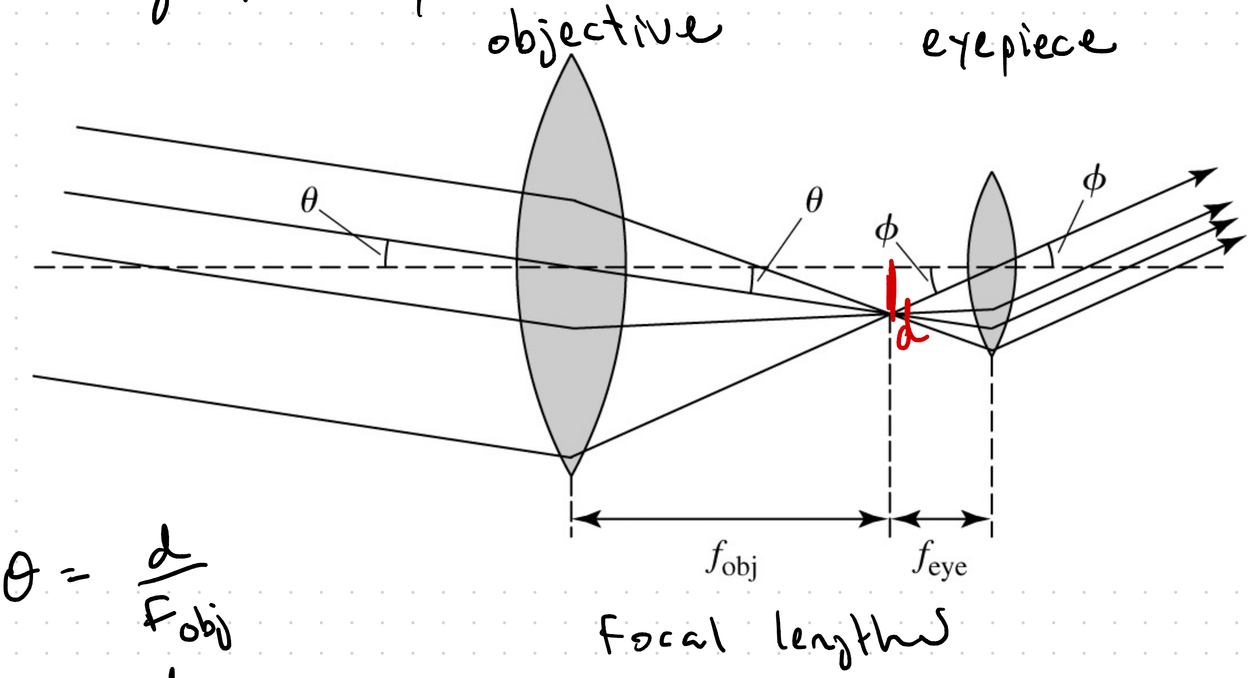
$$\theta = 206{,}265\,\frac{d}{F}$$

$$\frac{180^\circ}{\pi} \times \frac{3600''}{1^\circ}$$

plate scale

$$s = \frac{\theta}{d} = \frac{206265''}{F_{(mm)}}$$

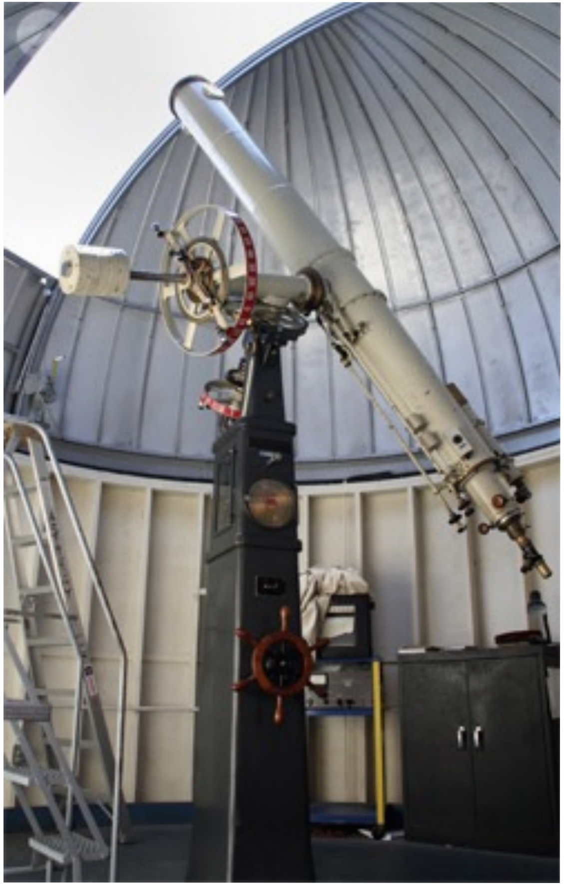
Refracting Telescope

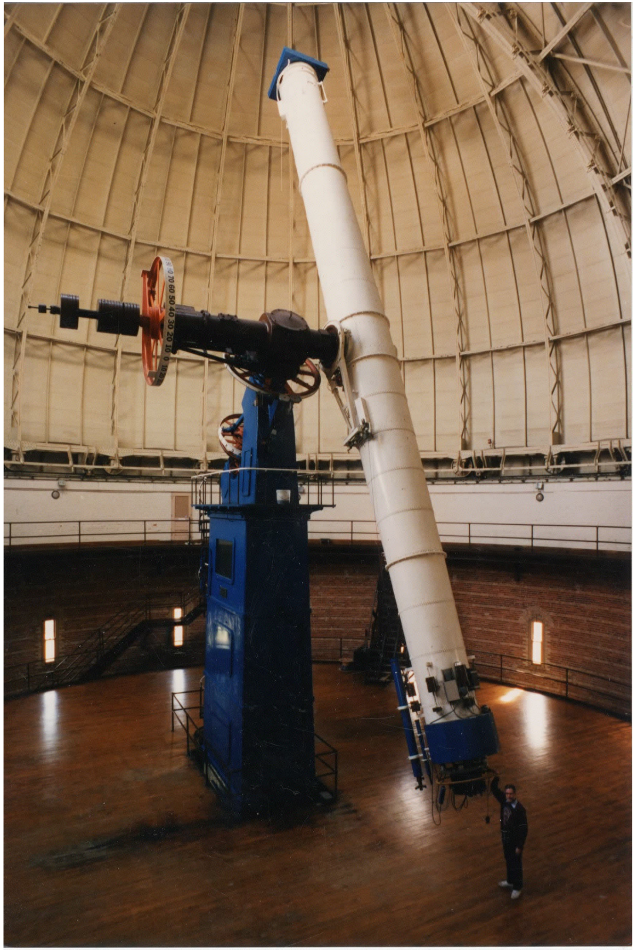


$$\tan\theta = \frac{d}{F_{obj}}$$

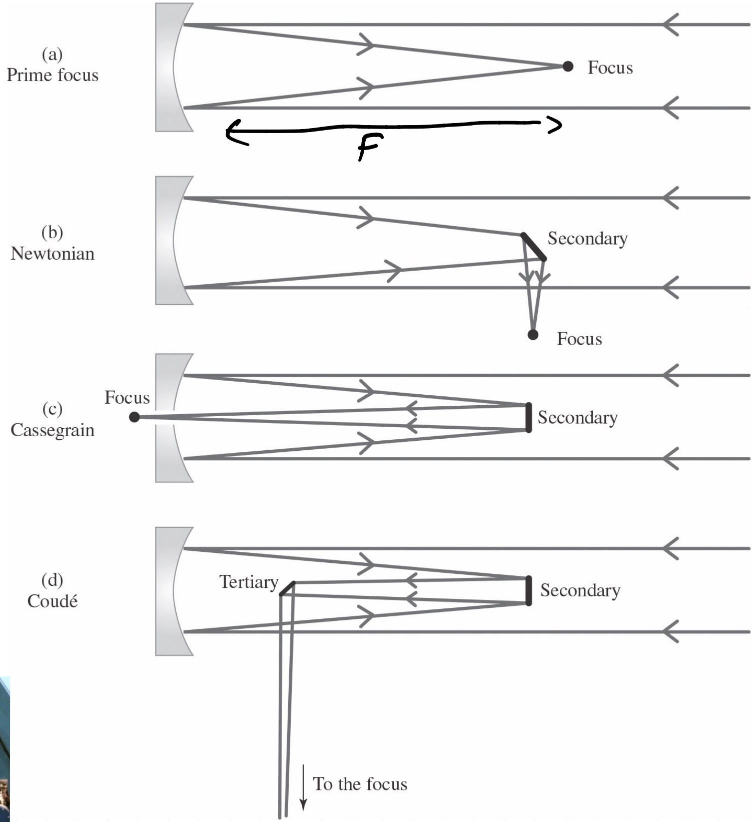
$$\tan\phi = \frac{d}{F_{eye}}$$

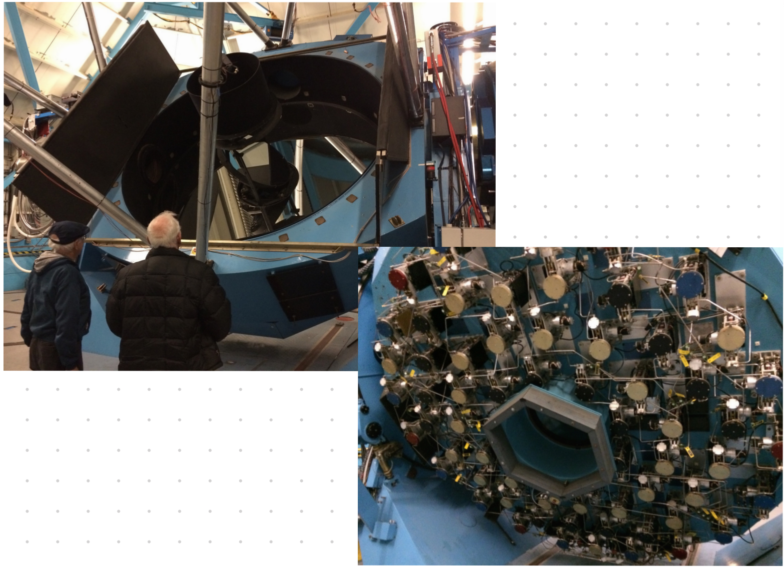
$$\frac{\phi}{\theta} = \frac{f_{obj}}{f_{eye}} = m$$ magnification

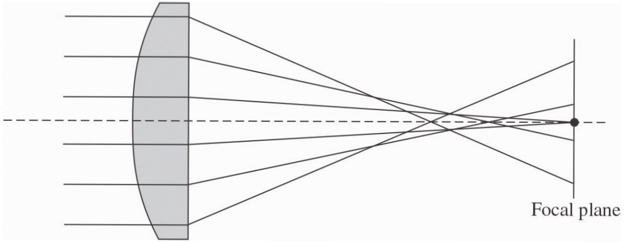



70 60 50 40 30 20 10 0

Reflecting telescope



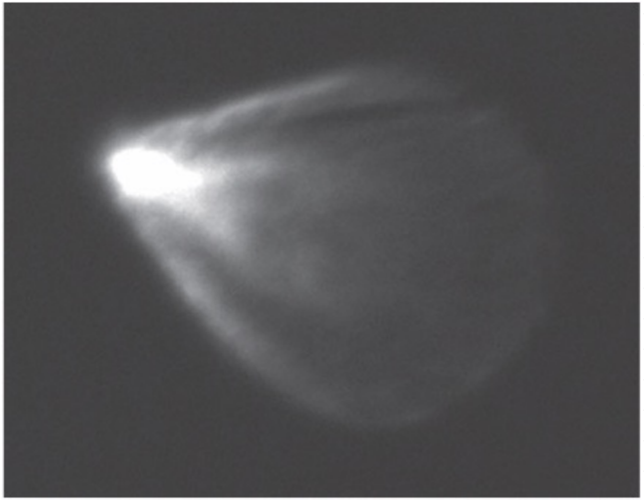


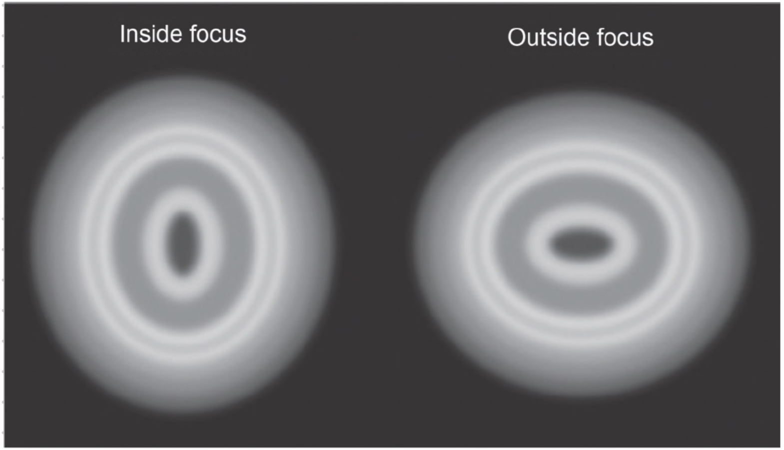


spherical abberation

astigmatism

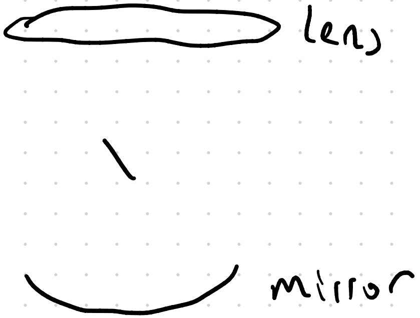
coma





Hybrid design

Schmidt-type



Ritchey-Chrétien

hyperboloid mirrors

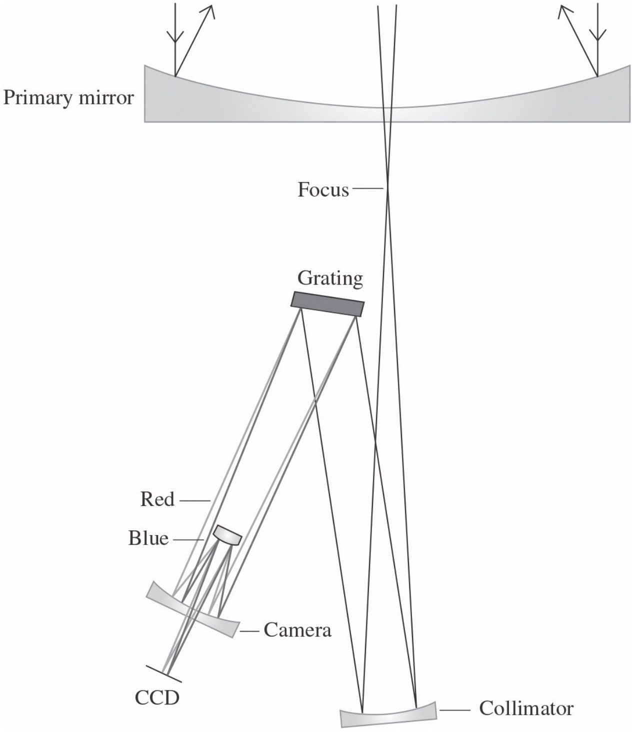
practical considerations

funding
geography
demand
clouds

damage
manufacturing
mounting design
type of observation

training
light pollution
atmosphere

Spectrographs



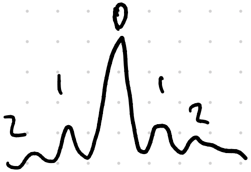
disperse light by wavelength

using prisms or gratings

gratings more common in modern applications → reflective

transmission

works by diffraction



$$d \sin \theta_m = m\lambda$$

slit spacing

angle of diffracted light

integer order

wavelength

Resolution $R = \dfrac{\lambda}{d\lambda}$

wavelength

distance between distinguishable features

Detectors

the human eye

photographic emulsions
(film / plates)

photoelectric effect devices

- photoemissive
  multiplier tubes
- photoconductive
  charge-coupled devices (CCDs)

Quantum Efficiency

"how many incident photons do you detect?"

eyes – [illegible] 1%

film – 1%

multiplier tubes – 10%

CCDs – 80%

over visible range

what are advantages of "artificial" detectors over the human eye?

CCDs

grids of capacitive "wells" that collect charge produced via photoelectric effect

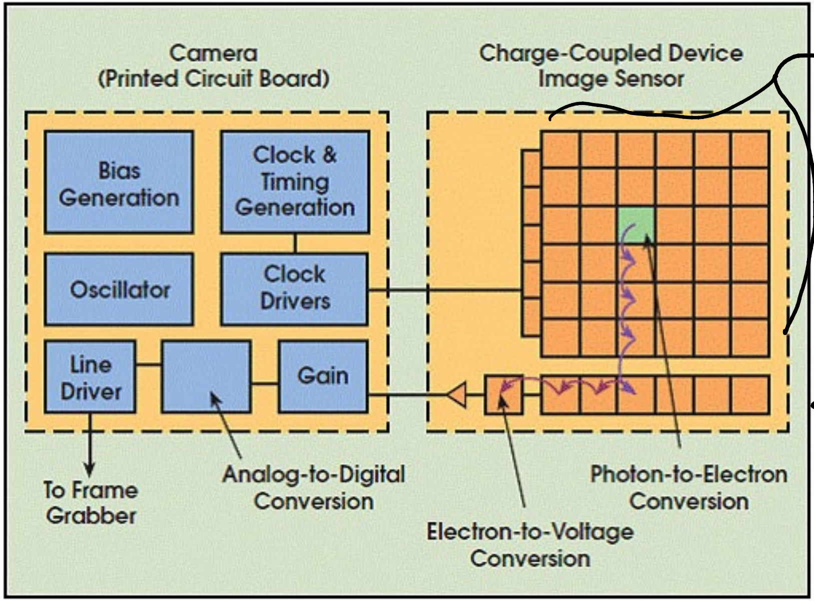


image detecting grid

photons → electrons

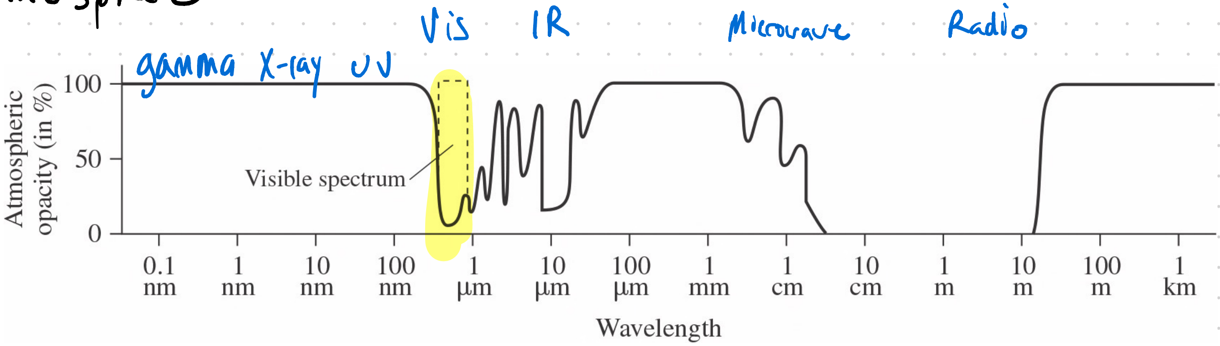
shift charge down by rows into

← readout register

then measure voltage in each column

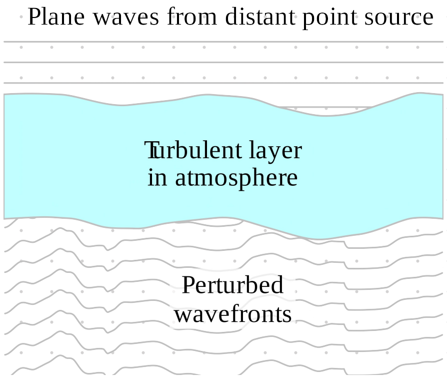
and convert to digital image

The Atmosphere



Most of EM spectrum is blocked by atmosphere

light that does make it through is blurred by atmospheric refraction producing an effect called "seeing"



turbulent layer always changing so amount of blurring constantly varies

Interferometry

Combining images from multiple telescopes to create an image with higher resolution.

usually used in radio astronomy to improve resolution at very long wavelengths $\theta_{min} = \frac{1{,}22\,\lambda}{D}$

Resulting image has same resolution as a single dish with size = separation between to smaller telescopes!

but not the same light gathering power!

Angular Size

1 full circle 360°

1 degree = $60'$

1 arcmin = $60''$

w/ small angle approx

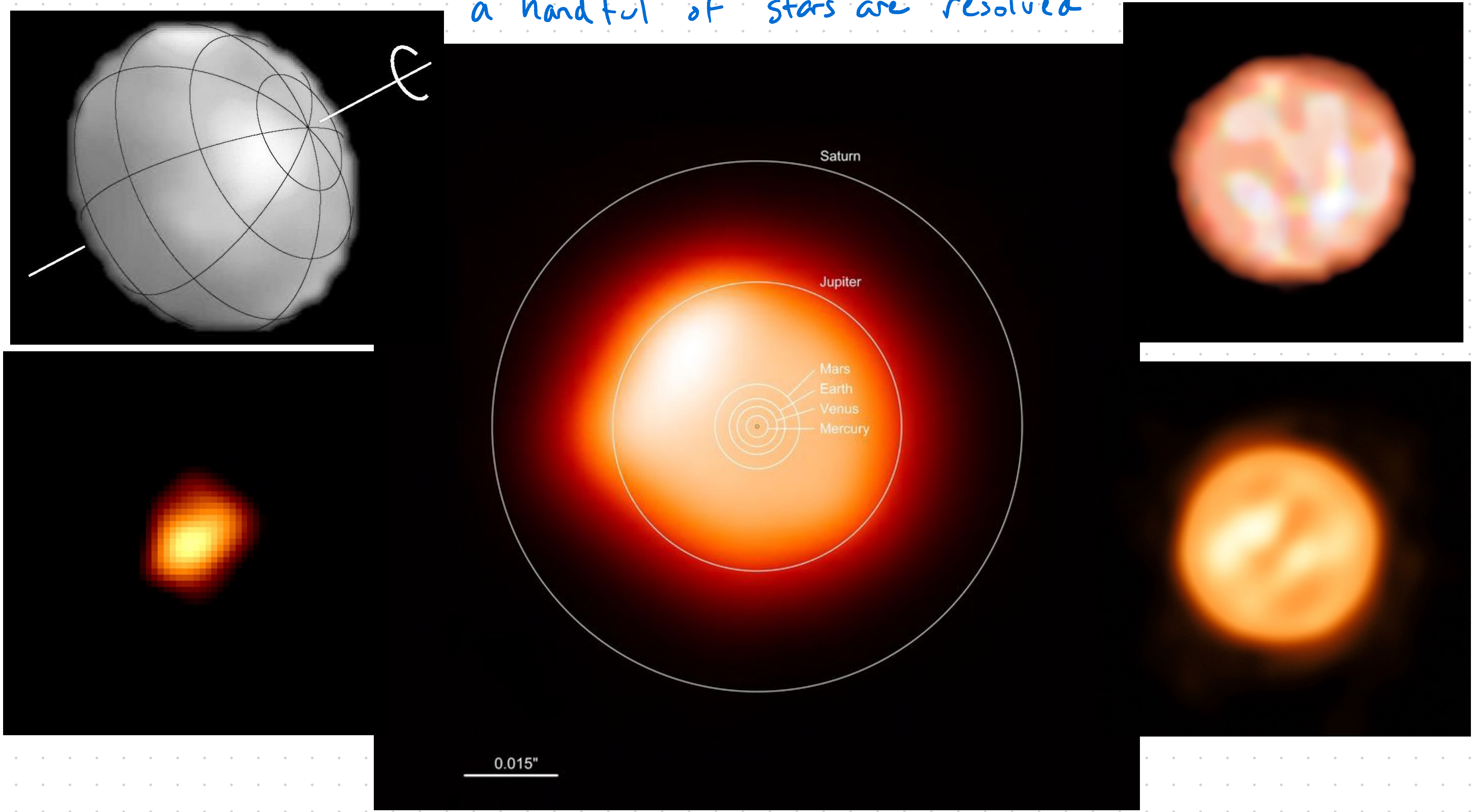
$$\frac{\text{physical size}}{\text{distance}} = \frac{\theta''}{206{,}265''/\text{rad}}$$

sizes of things in sky

sky	180°
big dipper	24°
thumb @ arms length	1°
moon | sun	$30' = 0.5^\circ$
Jupiter	$40''$

naked eye limit	$30''$	
atmospheric turbulence "seeing"	$1''$	$0.5''$
resolution limit HST	$0.1''$	
nearest star	$0.03''$	

a handful of stars are resolved



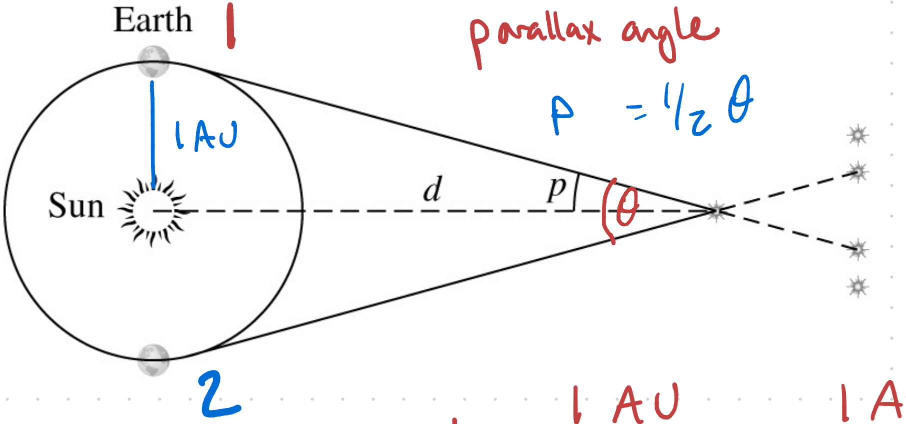
How would you measure distance in space?

trigonometric parallax

standard candle – something we know the luminosity of

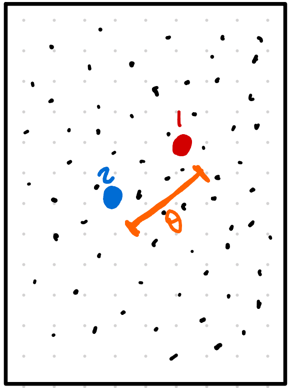
"spectroscopic parallax"

trigonometric parallax



parallax angle

$p = \frac{1}{2}\theta$



$$d = \frac{1\,AU}{\tan p} = \frac{1\,AU}{p}$$

in radians

$$d = \frac{206265''/\text{rad}}{p''} \quad \text{AU}$$

define a parsec

1 pc = 206,265 AU

$$\boxed{d = \frac{1}{p''} \text{ pc}}$$

parsec is distance when $p = 1''$

parallax arcsecond

nearest star
proxima cen
4.2 ly
$p = 0.77''$

1 pc = 3.26 ly

Smallest "possible" p = ~20 microarcsec ~ 0.00002''
≈ 50,000 pc

Brightness

Luminosity (W) $\begin{cases}\text{intrinsic property} \\ \text{total energy output of star}\end{cases}$

Brightness (W/m²) how bright the star appears observed from a given distance

aka "flux"

$$b = \frac{L}{4\pi d^2}$$

$L_{sun} = 3.8 \times 10^{26}$ W

$d = 1.5 \times 10^{11}$ m

$$b = \frac{3.8 \times 10^{26} \text{ W}}{4\pi(1.5 \times 10^{11} \text{ m})^2}$$

$= 1,344$ W/m²

"solar constant"

$$L = A\sigma T^4$$

$$= 4\pi R^2 \sigma T^4$$

Magnitudes

6 groups

100 x brightness ratio

- 1st brightest
- 2nd
- 3rd
- 4th
- 5th
- 6th faintest

human eye's response to light is logarithmic

groups separated by flux ratios, <u>not</u> differences

difference of 5 magnitudes equal to ratio of 100 in brightness

"logarithmic scale"

$$\frac{b_1}{b_2} = 100^{(m_2 - m_1)/5} = 100^{5/5} = 100^1 = 100$$

$$= 100^{10/5} = 100^2 = 10{,}000$$

$$= 100^{1/5} = 100^{0.2} = 2.512$$

$$b = \frac{L}{4\pi d^2}$$

$$L = A\sigma T^4 = 4\pi R^2 \sigma T^4$$

$$\frac{b_1}{b_2} = 10^{2(m_2-m_1)/5}$$

$$b_1/b_2 = 10^{0.4(m_2-m_1)} = 10^{(m_2-m_1)/2.5}$$

$$\log_{10}(10^{(m_2-m_1)/(2.5)} = \log_{10}\frac{b_1}{b_2}$$

$$m_2-m_1/2.5 = \log_{10} b_1/b_2$$

why?

$$m_2-m_1 = 2.5\log_{10} b_1/b_2$$

$$m_2-m_1 = -2.5\log_{10} b_2/b_1$$

Spectroscopic parallax

magnitudes

log scale

Δm = flux ratios

$\Delta m = 5 \rightarrow 100 : 1$ brightness

$\Delta m = 1 \rightarrow 100^{1/5} : 1 = 2.512 : 1$

smaller apparent magnitudes (more negative) are brighter

Sun	-26.8
Sirius	-1.46
Vega	0.0000000000
naked eye limit	$\sim +6$
theoretical limit for current modern telescopes	$+29$

$$m_1 - m_2 = -2.5 \log\left(f_1/f_2\right)$$

m apparent magnitude $b = \frac{L}{4\pi d^2}$

M absolute magnitude $b = \frac{L}{4\pi(10\text{pc})^2}$

$$m - M = -2.5 \log_{10}\left(\frac{\frac{L}{4\pi d^2}}{L/4\pi(10)^2}\right)$$

$$m - M = -2.5 \log_{10}\left(\frac{\frac{\cancel{1}}{\cancel{4\pi} d^2}}{\frac{\cancel{1}}{\cancel{4\pi}(10)^2}}\right)$$

$$-\log\left(\frac{1}{x^2}\right) = +2 \log x$$

$$m - M = -2.5 \log_{10}\left(\frac{10^2}{d^2}\right)$$

$$\log\left(\frac{x}{y}\right) = \log x - \log y$$

$$m - M = -2.5 \log(10^2) + 2.5 \log(d^2)$$

$$m - M = -5 \cancelto{1}{\log(10)} + 5 \log d$$

$$m - M = 5 \log d - 5$$ distance modulus

↑ d in parsecs

$$M_{sun} = 4.76$$

Adding Magnitudes

$m_1 + m_2$

$m_1 = -2.5 \log(L_1 / 4\pi d_1^2)$

$m_2 = -2.5 \log(L_2 / 4\pi d_2^2)$

The Sun

what do you know about the Sun?

93 million miles away

150 million km

powered by nuclear fusion

totally average

onion structure

magnetic field

eject matter

orbiting around Galaxy

spin / rotate

$R_\odot$

$H \rightarrow He$

$T_{eff} = 5780\ K$ "surface temp"

pale yellow

$R_\odot = 6.96 \times 10^5\ km$ = 1 solar radius

$L_\odot = 3.9 \times 10^{26}\ W = 10^{33}\ erg/s$

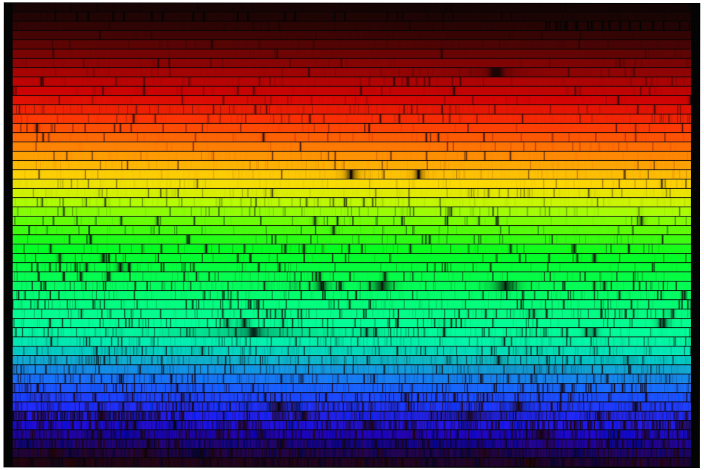
1 solar Luminosity

$M_\odot = 1.99 \times 10^{30}\ kg$ = 1 solar mass

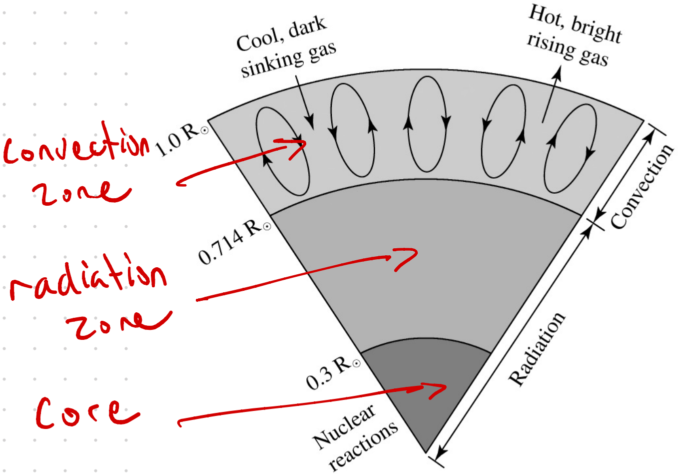
chemical composition

by mass	by #
70% H	92.1 % H
28% He	7.8 % He
2 % everything else	0.1 % "metals"

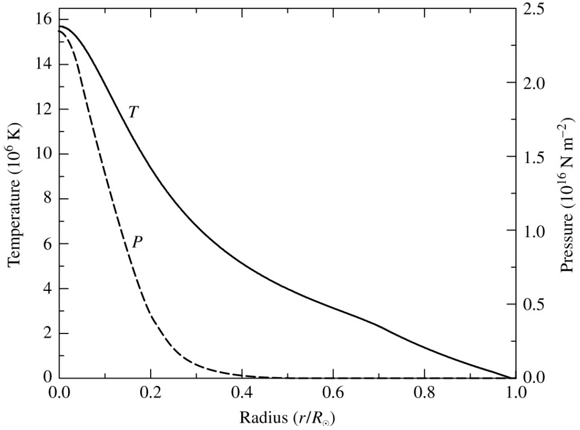
O, N, C, Fe, Mg, Si "Metal"

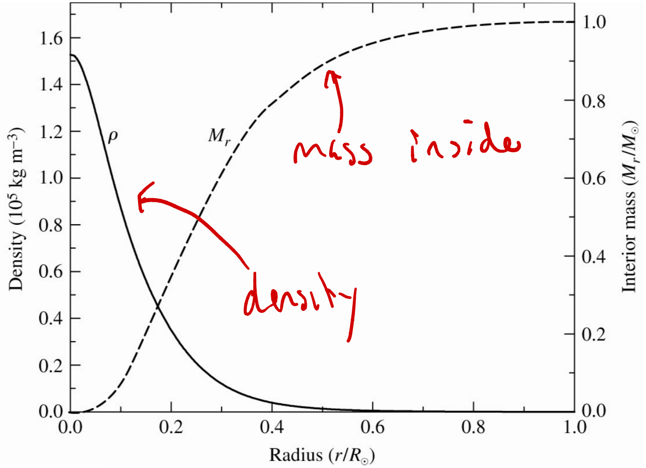


mean density 1,440 kg/m³



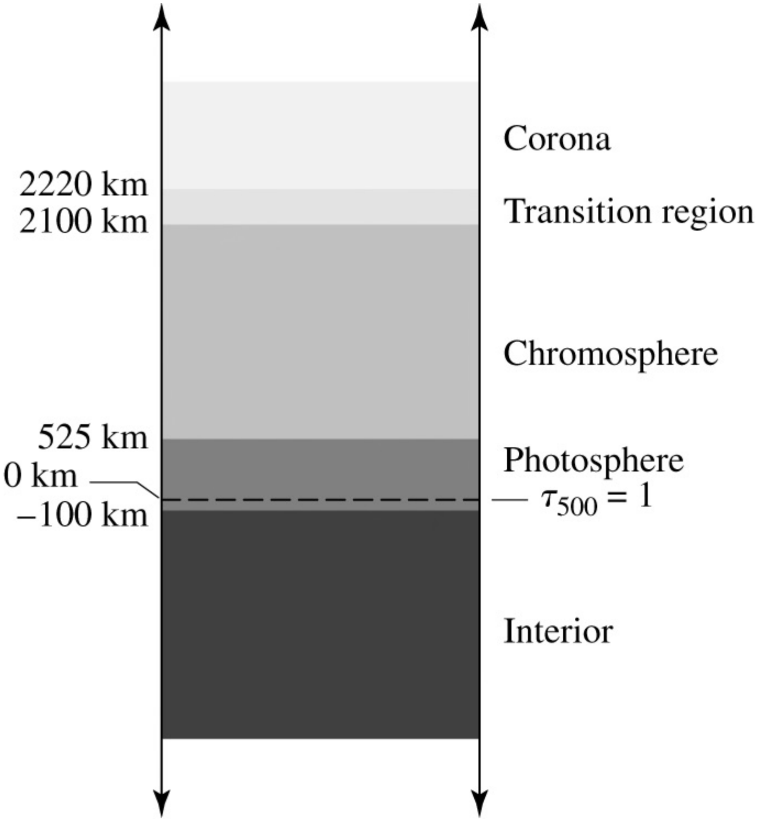
interior temp/pressure





mass inside

density



HW 3

due 11:59pm

10/11

Midterm

10/13

in class

Observing

Night

8pm

10/13

14 or 15

Corona

during

total

solar

eclipse

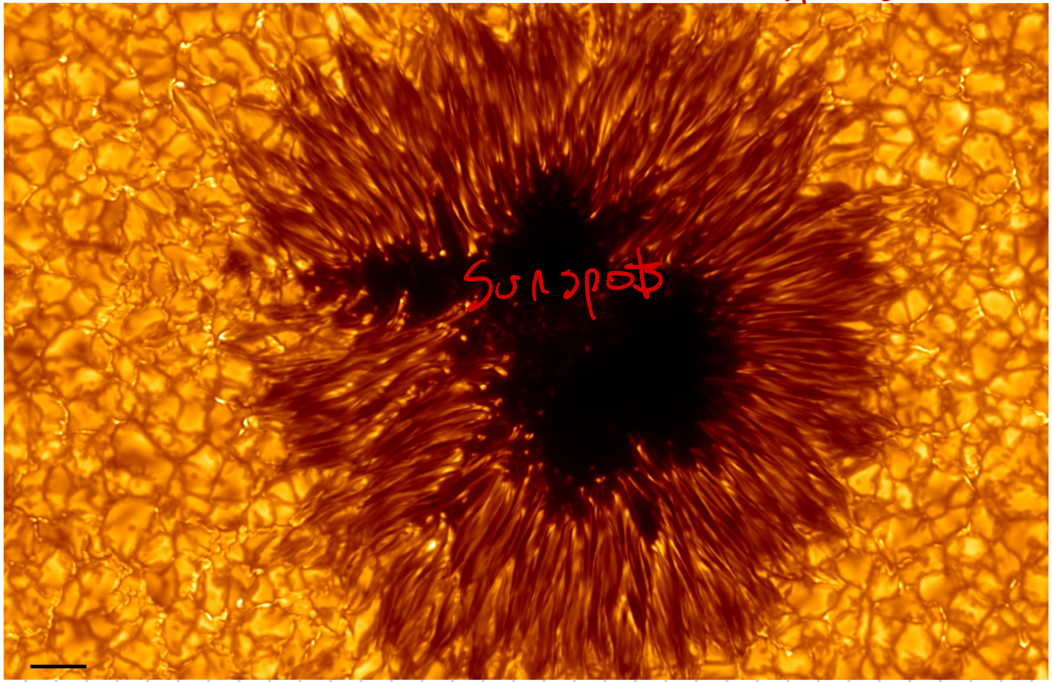
$L = A\sigma T^4$

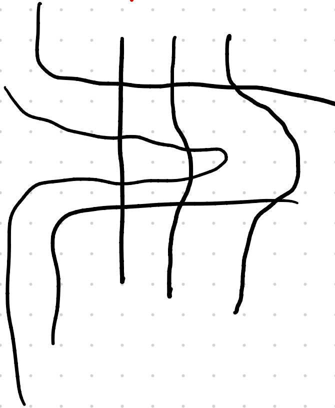
sunspots → magnetic field lines

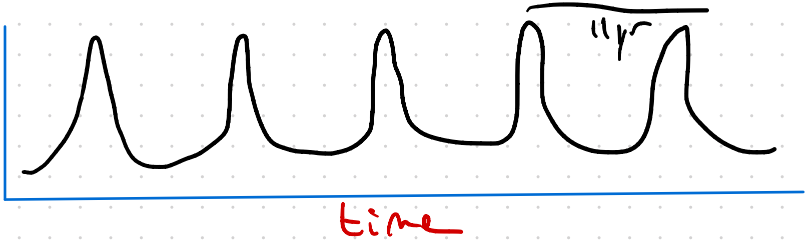
inhibit convection

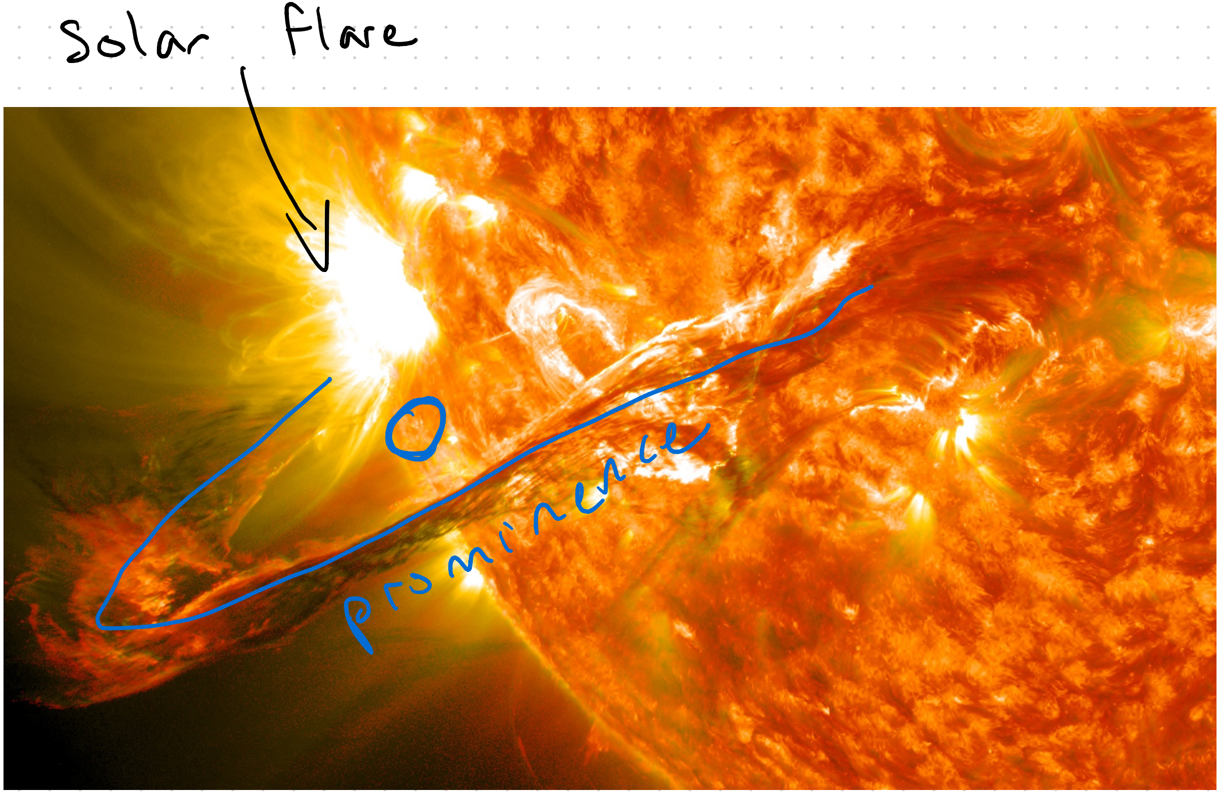
cooler areas are darker

granules



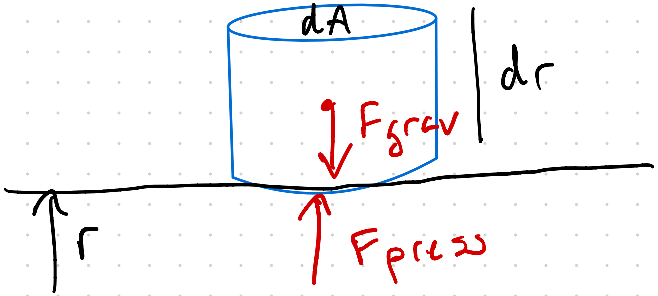





Solar flare
prominence

Hydrostatic Equilibrium

gravity vs. pressure



density = $\rho(r)$

volume = $dr\, dA$

mass $dm = \rho(r)\, dr\, dA$

$$F_{grav} = \frac{-GMm}{r^2} = \frac{-G\, M(r)\, dm}{r^2}$$

$$= \underbrace{\frac{-GM(r)}{r^2}}_{g(r)} \rho(r)\, dr\, dA$$

$$F_{grav} = -g(r)\rho(r)\, dr\, dA$$

net pressure $= P(r+dr) - P(r)$

$$F_{press} = (P(r+dr) - P(r))\,dA = \underline{dP\,dA}$$

$$F_{press} = F_{grav}$$

$$dP\,\cancel{dA} = -g(r)\,\rho(r)\,dr\,\cancel{dA}$$

$$dP = -g(r)\,\rho(r)\,dr$$

$$\frac{dP}{dr} = -g(r)\rho(r) = -\frac{G M(r)\rho(r)}{r^2}$$

Central Pressure

assume $\langle \rho \rangle = 1440 \ kg/m^3$

$$M(r) = \frac{4}{3}\pi r^3 \langle \rho \rangle$$

$$\frac{dP}{dr} = -\frac{G M(r) \rho(r)}{r^2} = -\frac{4}{3} G \pi \frac{r^3 \langle \rho \rangle \langle \rho \rangle}{r^2}$$

$$\frac{dP}{dr} = -\frac{4}{3}\pi G r \langle \rho \rangle^2$$

$$\int_{P_c}^{0} dP = -\frac{4}{3}\pi G \langle \rho \rangle^2 \int_0^R r \, dr$$

↑
central pressure

$$-P_c = -G \, 4/3 \pi \langle \rho \rangle^2 \frac{1}{2} R^2$$

$$P_c = \frac{2}{3}\pi G \langle\rho\rangle^2 R^2$$

$$P_c = 2.5 \times 10^{16}\ N/m^2$$

→ 250 billion atm

Mariana Trench

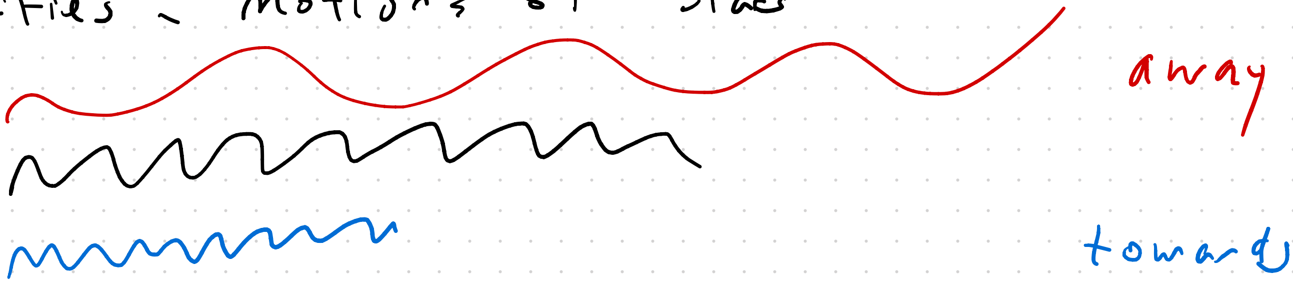
1,070 atm

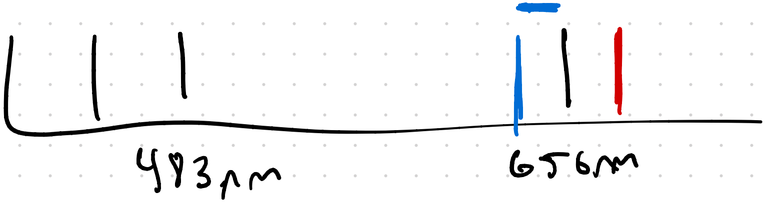
$T = 15$ million K

how do we know the mass of the sun?

$$P^2 = \frac{4\pi^2}{GM} a^3$$

Velocities ~ motions of stars





$$\frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} = z$$

"redshift"

$$z = \frac{V_r}{c}$$ velocity

"proper motion"

HW 3 Equation Reminders

$$\boxed{d = \frac{1}{p''} \quad \text{in parsecs, arcseconds}}$$

parallax distances

magnitudes/fluxes

$$\boxed{\begin{aligned} m &= -2.5 \log f \\ & \qquad\qquad\quad \updownarrow \\ &= -2.5 \log\left(\frac{L}{4\pi d^2}\right) \end{aligned}}$$

$$\boxed{\begin{array}{ccccc} m & - & M & = & 5 \log_{10} d - 5 \\ \text{apparent} & & \text{absolute} & & \text{in parsecs} \\ & & \text{magnitude} & & \end{array}}$$

distance modulus

$$\boxed{m_1 - m_2 = -2.5 \log f_1/f_2}$$

magnitude differences

$$\frac{x}{d} = \frac{\theta''}{206{,}265''}$$

$$\boxed{L = 4\pi R^2 \sigma T^4}$$

luminosity

$$\boxed{P^2 = \frac{4\pi^2}{G(M_1+M_2)} a^3}$$

Keplers 3rd Law

$G = 4\pi^2$

in AU

yr

$M_\odot$

"proper motion"

measure side-to-side velocity

typically measure w/ parallax

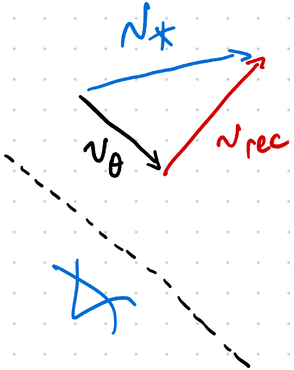
→ change in sky position over time

μ = PM in "/year

$$= \frac{d\theta}{dt} = \frac{v_\theta}{d}$$

$$v_\theta = 4.74 \mu d$$

$[km/s]$ $["/yr][pc]$



therefore "true space motion"

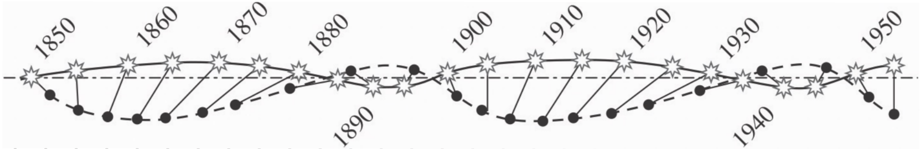
$$v_*^2 = v_{rec}^2 + v_\theta^2$$

Binary Stars (+ exoplanets)

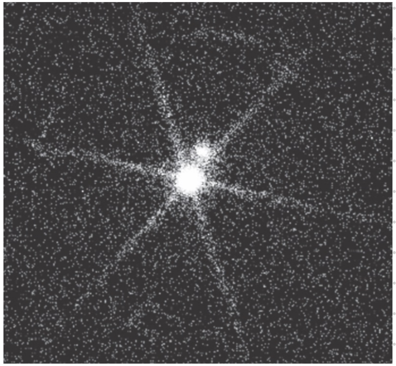
get mass from observing orbits

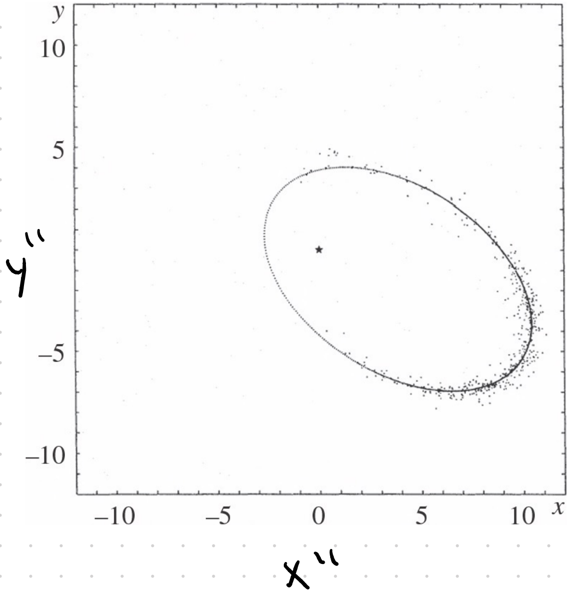
50% of all stars in binary (or bigger) systems

Visual Binaries



Sirius A+B



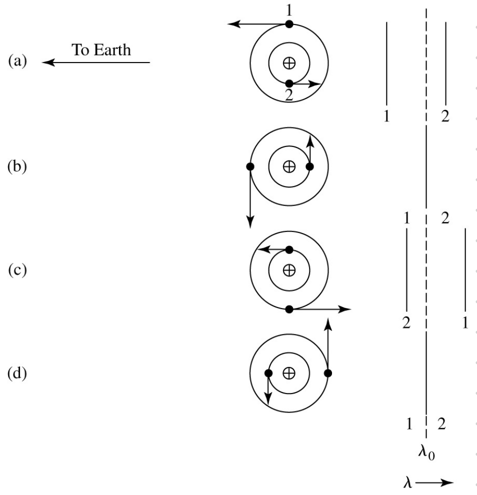


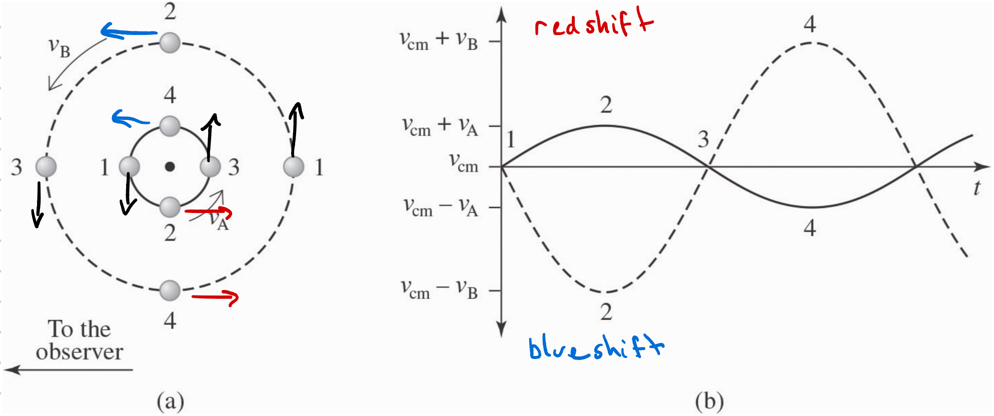
stars need to be close or far apart to resolve orbits

usually takes decades to get high quality data

Spectroscopic Binaries

observe shifting spectral features in stellar spectra to reconstruct velocity curves





$$v_A M_A = v_B M_B \Rightarrow \frac{M_B}{M_A} = \frac{v_A}{v_B}$$

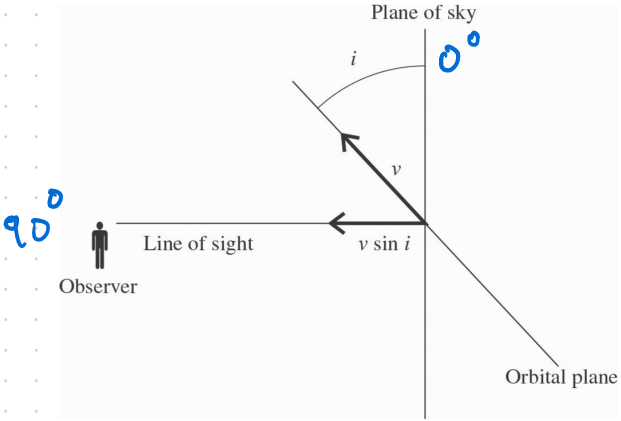
$$P = \frac{2\pi a_A}{v_A} = \frac{2\pi a_B}{v_B}$$

$$a = \frac{Pv}{2\pi}$$

$$P^2 = \frac{4\pi^2}{G(M_A+M_B)}(a_A+a_B)^3$$

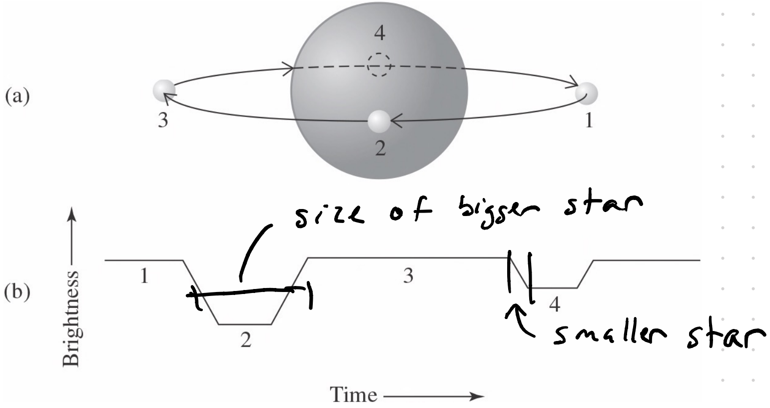
$$P^2 = \frac{4\pi^2}{G(M_A+M_B)} \frac{P^3(v_A+v_B)^3}{(2\pi)^3}$$

$$M_A + M_B = \frac{P}{2\pi G} \frac{(v_A+v_B)^3}{\sin^3 i}$$



$v_{true} = v \sin i$

Eclipsing Binaries



Mass of a star is the fundamental defining property

$L \propto M^4$

Initial Mass Function

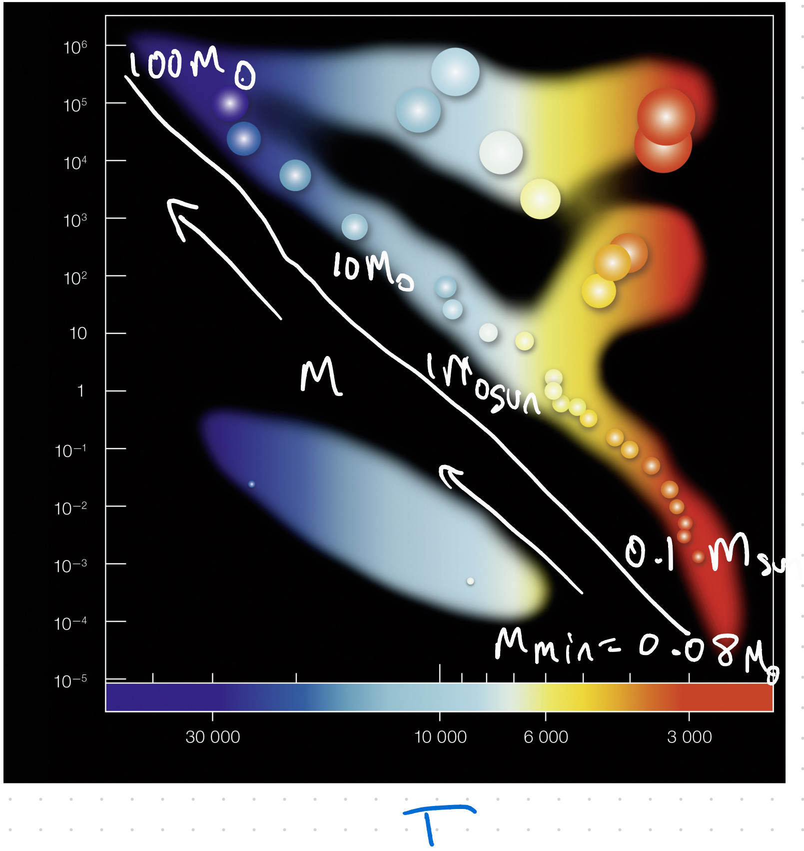
More massive stars less common L

100 : 1

1 $M_\odot$: 10 $M_\odot$

main sequence lifetime

$t_{MS} \propto \frac{1}{M^{2.5}}$



Nuclear Fusion

4 Hydrogen → 1 Helium

● protons

● neutrons

● electrons

Atomic Mass Unit

1 AMU = $1/12$ carbon atom = 1.66×10^{-27} kg

$$E = mc^2$$

$= 931.5$ million electron Volts (MeV)

1 eV = 1.6×10^{-19} J

$M_H - M_p - M_e = -13.6$ eV

binding energy

H + energy = proton + electron

$4H - 1\,He = +26.71$ MeV

0.7% of total mass

$$E = 0.007\,(0.1 \times M_\odot)\,c^2$$

$$= 1.3 \times 10^{43}\ J\,/\,L_\odot$$

$$= 10^{10}\ \text{years}$$

Class Telescope Night Wed @ 8pm

Midterm also Wed in class

don't forget your "cheat" sheet

Proton - Proton Chain

proton → ^1H

$^4He \rightarrow 2p + 2n$

$T > 10$ million K

step 1

deuterium = 1p+1n

$$^1H + ^1H \Rightarrow ^2H + e^+ + \nu$$

positron neutrino

step 2

$$^2H + ^1H \Rightarrow ^3He + \gamma$$

= 2p+1n

gamma ray photon

repeat step 1 & step 2

$2\,^3He$

Step 3:

most common 69% of the time

PPI $^3He + ^3He \Rightarrow ^4He + ^1H + ^1H$

31% of time

$^3He + ^4He \Rightarrow ^7Be + \gamma$

^4He = alpha

PPII $^7Be + e^- \rightarrow ^7Li + \nu$

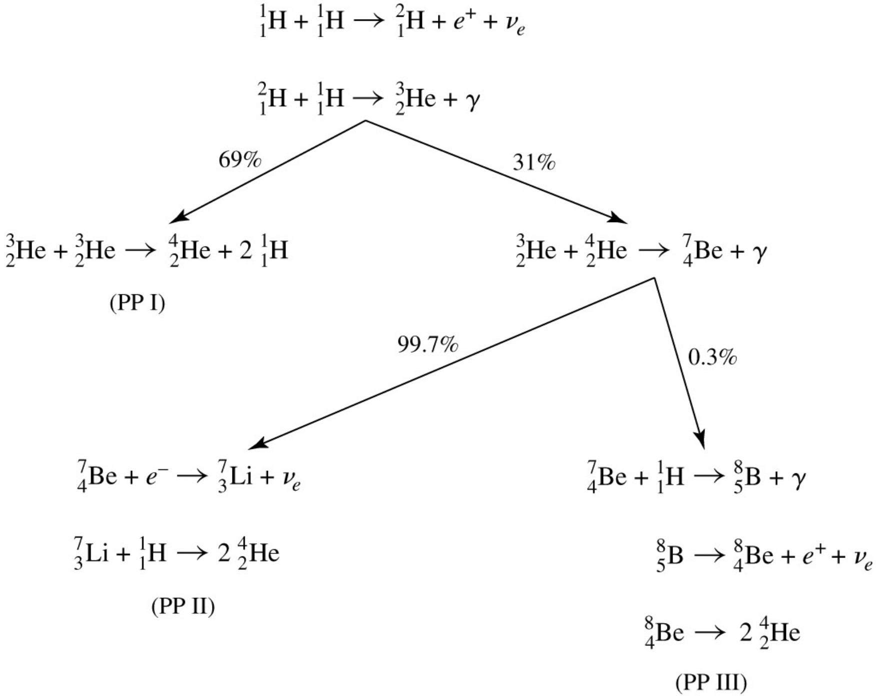
$^7Li + ^1H \Rightarrow ^4He + ^4He$

0.3% of the time

$^7Be + ^1H \Rightarrow ^8B + \gamma$

spallation?

PPIII $^8B \Rightarrow ^8Be + e^+ + \nu$ // $^8Be \Rightarrow ^4He + ^4He$


$^1_1H + ^1_1H \longrightarrow ^2_1H + e^+ + \nu_e$
$^2_1H + ^1_1H \longrightarrow ^3_2He + \gamma$
69%
31%
$^3_2He + ^3_2He \longrightarrow ^4_2He + 2\,^1_1H$
(PP I)
$^3_2He + ^4_2He \longrightarrow ^7_4Be + \gamma$
99.7%
0.3%
$^7_4Be + e^- \longrightarrow ^7_3Li + \nu_e$
$^7_3Li + ^1_1H \longrightarrow 2\,^4_2He$
(PP II)
$^7_4Be + ^1_1H \longrightarrow ^8_5B + \gamma$
$^8_5B \longrightarrow ^8_4Be + e^+ + \nu_e$
$^8_4Be \longrightarrow 2\,^4_2He$
(PP III)

10^{57}

10^{56}

10^{55}

10^{45}

$10^{39} \times 26$ MeV

10^{39} MeV/s

HW 4 now due 11/15 ~~15.5~~ → 15.7

HW 5 now due 11/15

p-p chain

$4\,{}^{1}H \rightarrow {}^{4}He + \gamma$

$T_{core} > 10$ million K

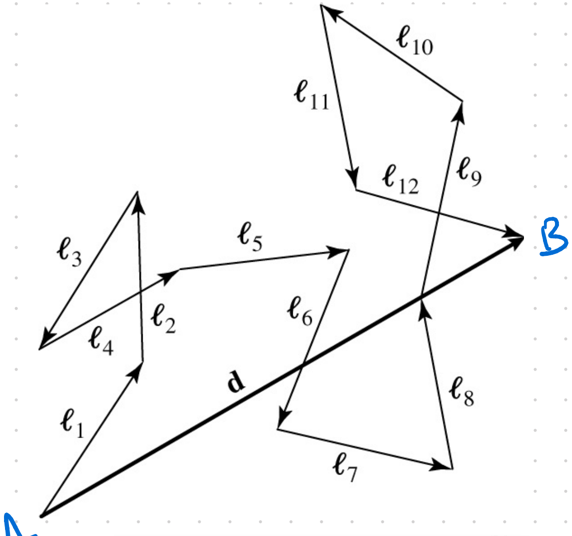
$= 15$ million K

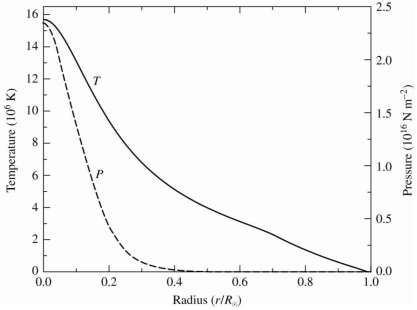
$T_{surf} = 5200$ K

How do we go from high energy γ-rays @ 15 million K to visible light @ ~ 6000 K?

convection radiation

random walk





mean free path ℓ

number of steps N

$$d = \ell\sqrt{N}$$

$$N = \left(\frac{d}{\ell}\right)^2$$

$\ell = 10^{-3}$ m

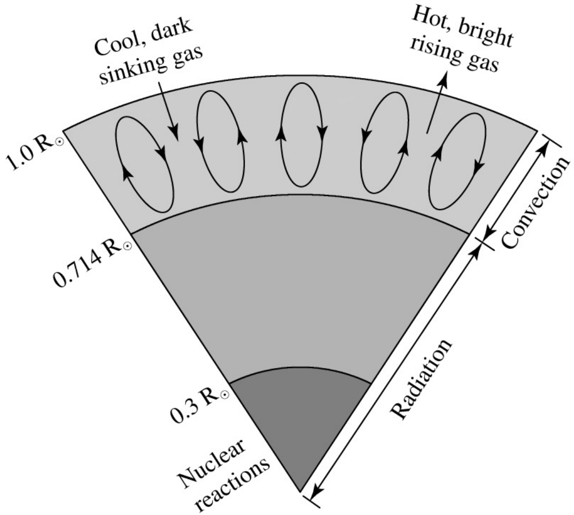
$d = R_{sun} = 7 \times 10^5$ km

$N = 10^{22}$

$t = 50,000$ years

convection

- hot gases rising, cool gases falling
- bulk motion of "cells" of gas
- net energy transport of energy from bottom to top
- no net transport of mass



Opacity (opaque)

mean free path depends on

- λ of light
- density
- temperature
- ionization / excitation states of atoms

inner regions dense, high T, high ionization, short λ

outer regions low density, low T, low ionization, long λ

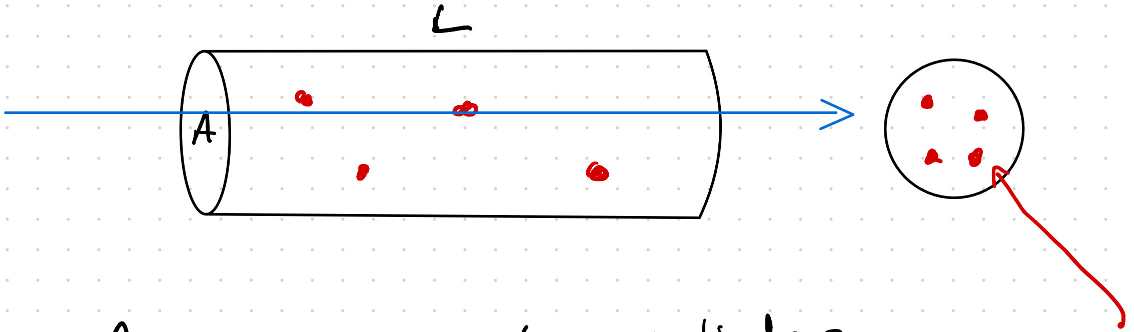
when opacity is very high, energy is more efficiently transported by convection

radiation

$$\frac{dT}{dr} = \frac{3\rho(r)\,\overset{\text{opacity}}{\kappa(r)}\,L(r)}{64\pi\sigma_{SB}T(r)^3\,r^2}$$

convection

$$\frac{dT}{dr} = \Big(1 - \frac{1}{\underset{\text{adiabatic index}}{\gamma}}\Big)\frac{T(r)}{P(r)}\frac{dP}{dr}$$



$\sigma_a = \pi r^2$

A = area of cylinder

L = length

r = size of absorbers

n = number density of absorbers

$V = L A$

$N = n L A$

$\sigma_{tot} = n L A \sigma_a$

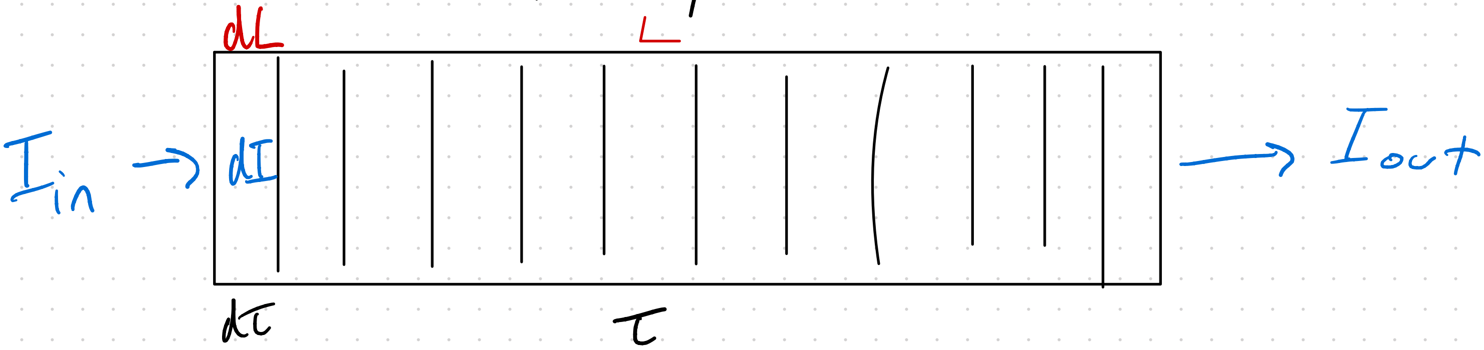
fraction absorbed

"optical depth"

$$F_{abs} = \frac{\sigma_{tot}}{A} = n L \sigma_a = \tau$$

small τ "optically thin"

large τ "optically thick"



$$dI = -(I)(n\sigma dL) = -I\,d\tau$$

$$\frac{dI}{I} = -d\tau \qquad \int_{I_{in}}^{I_{out}} \frac{dI}{I} = -\int_0^{\tau} d\tau$$

$$\ln\left(\frac{I_{out}}{I_{in}}\right) = -\tau \qquad I_{out} = I_{in}\, e^{-\tau}$$

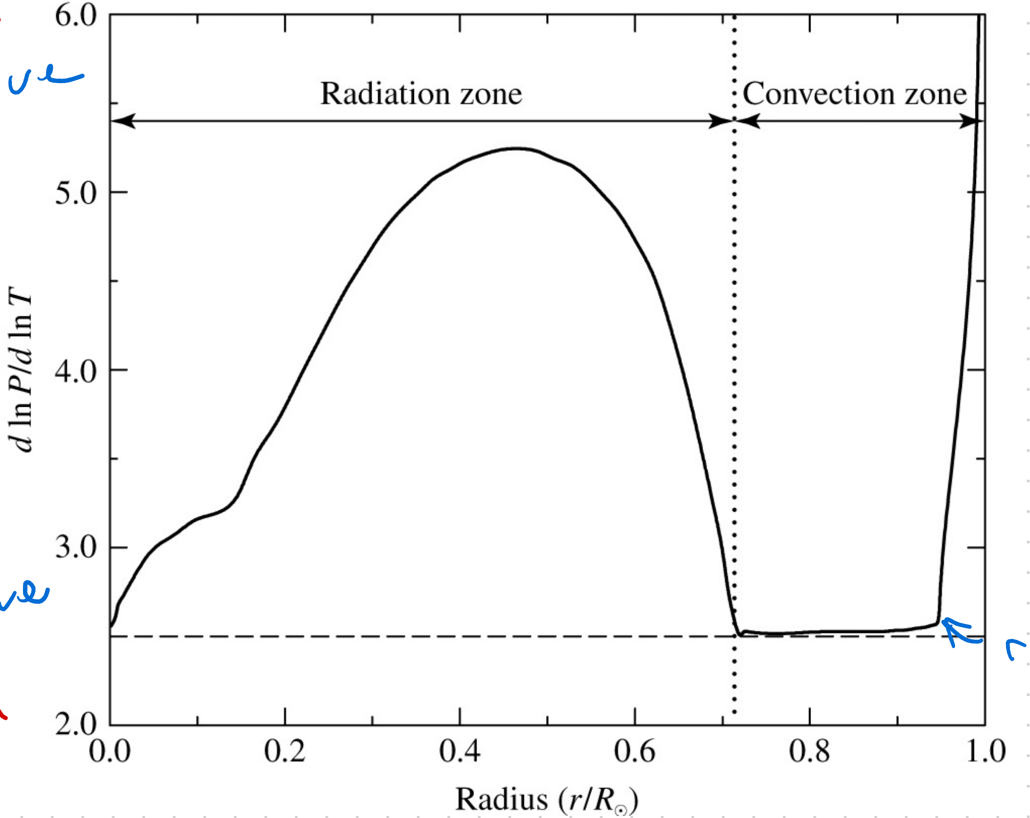
radiation

less opaque

$\frac{1}{\tau} =$

more opaque

convection



surface

$\tau = 2/3$

radiation

Stellar Evolution

energy production (fusion)

energy transport (radiation, convection) opacity

gravity
radiation pressure } hydrostatic equilibrium $\frac{dP}{dr} = -\rho(r) g(r)$

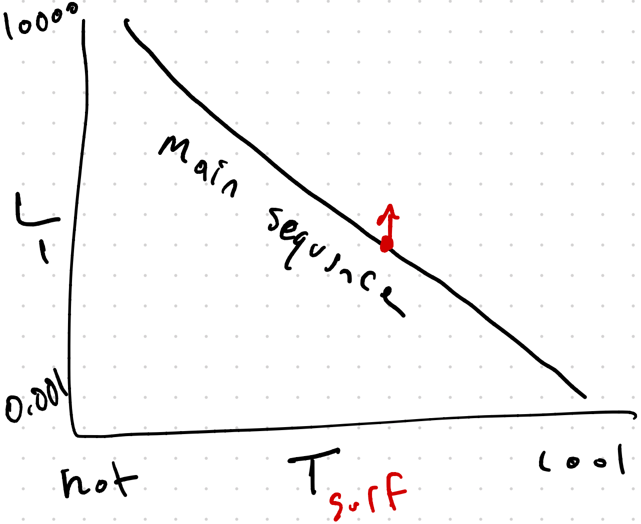
equation of state $PV = NkT \Rightarrow P = \frac{\rho k T}{\mu m_H}$

"mean molecular weight

chemical composition

X	H	0.7
Y	He	0.28
Z	"metals"	0.02

MASS is the most important determining factor



" period of a stars life when it fuses H to He in the core "

$$P = \frac{\rho k T}{\mu m_H} \quad \text{core}$$

what changes do we expect to see as H → He ?

energy generation rate

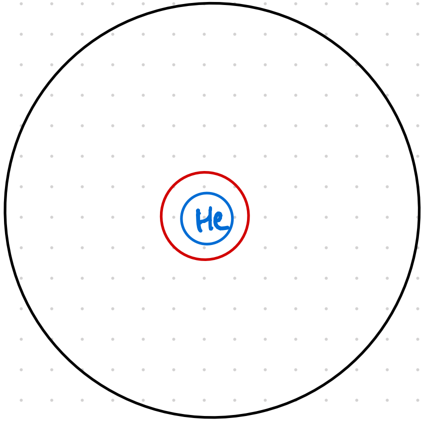
$$\epsilon_{pp} \sim T^4$$

$$L = 4\pi R^2 \sigma T_{\text{surface}}^4$$

$$L_{\text{now}} = 1.4 \times L_{\text{initial}}$$

main sequence lifetime

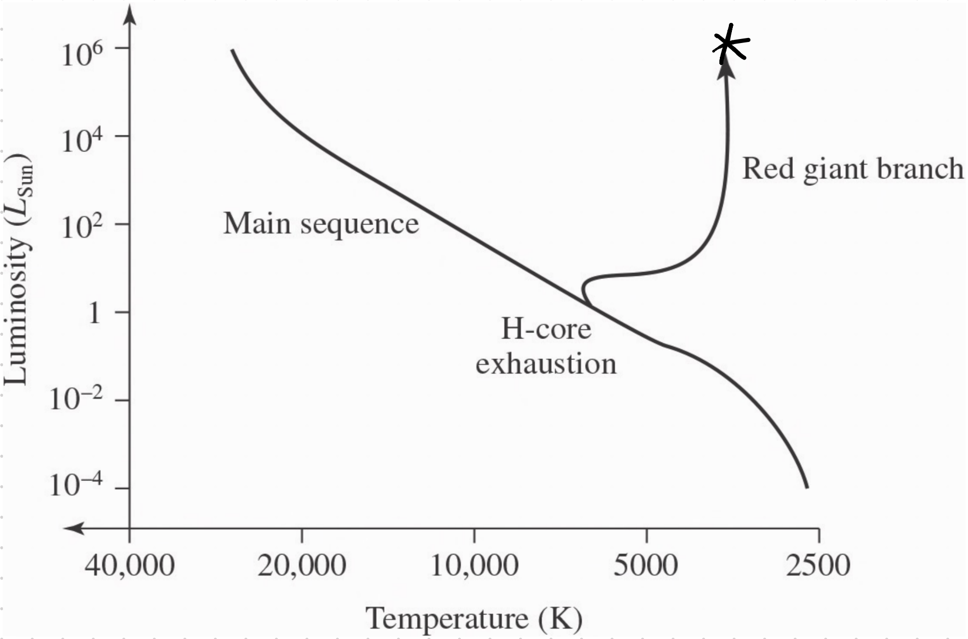
$$t_{ms} \simeq \frac{1}{M^{2.5}} = 10 \text{ Gyr}$$



core contracts → T_{core} increases

H → He shell burning

Red Giant Branch



Red Giants

$L > 100 L_{sun}$

$T \sim 4000$ K

$R \sim 30 - 300 R_{sun}$

degeneracy pressure keeps core from collapsing

electrons keep core supported instead thermal pressure

$$P_e \sim \rho^{5/3}$$

helium flash @ 100 million K in core

triple alpha process $\alpha = {}^4He$

$${}^4He + {}^4He \rightarrow {}^8Be$$

$${}^8Be + {}^4He \rightarrow {}^{12}C + \gamma$$

$$\epsilon_{3\alpha} \sim T^{41}$$

$${}^{12}C + {}^4He \rightarrow {}^{16}O + \gamma$$

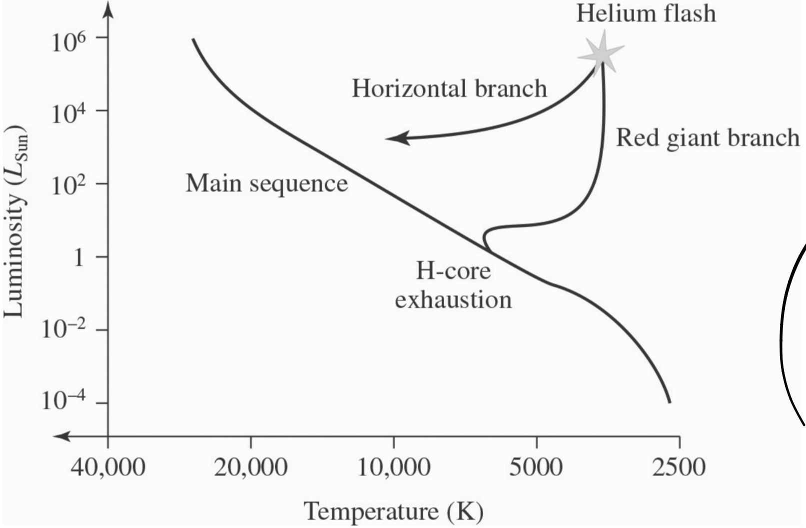
$${}^{16}O + {}^4He \rightarrow {}^{20}Ne + \gamma$$

release 10^{11} L_{sun} all at once (few seconds)

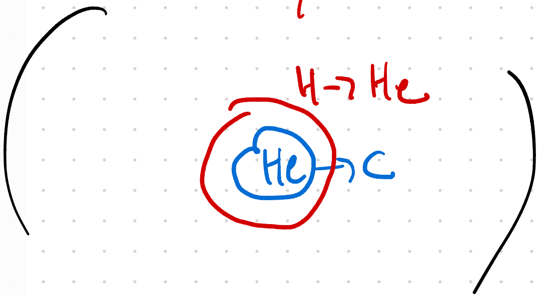
none makes it out of star

all the photons break electron degeneracy pressure, return star to ideal gas

expands core



Helium-burning main sequence = horizontal branch



what happens when you run out of Helium in the core?

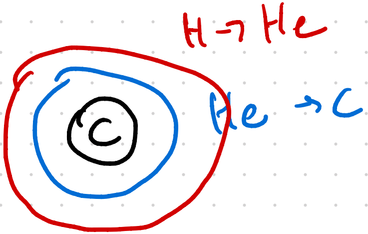
core will contract, but supported by degeneracy pressure

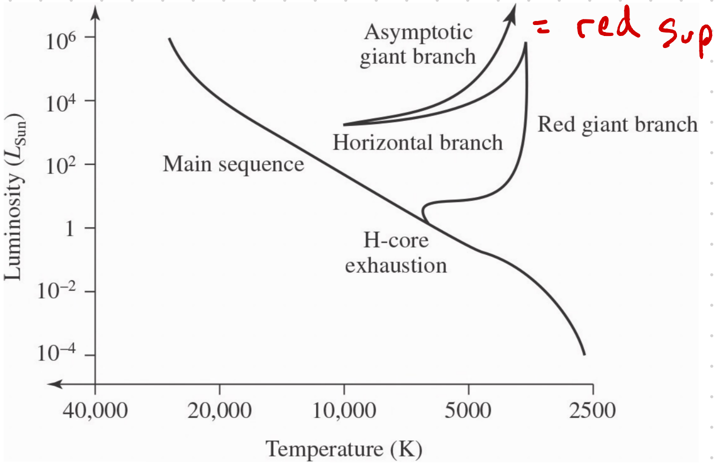
core T increases

Star gets bigger, surface cools down

H^- ion

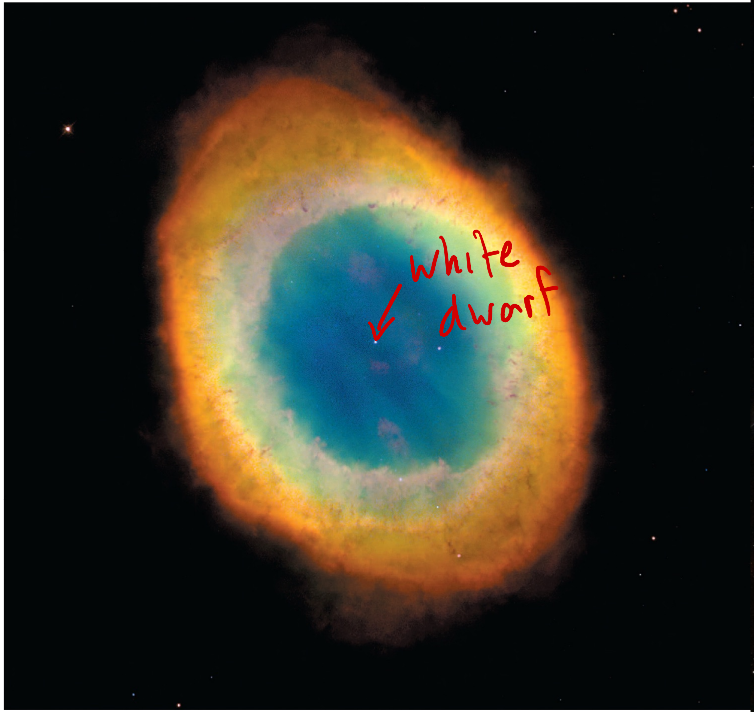
$p + 2e^-$

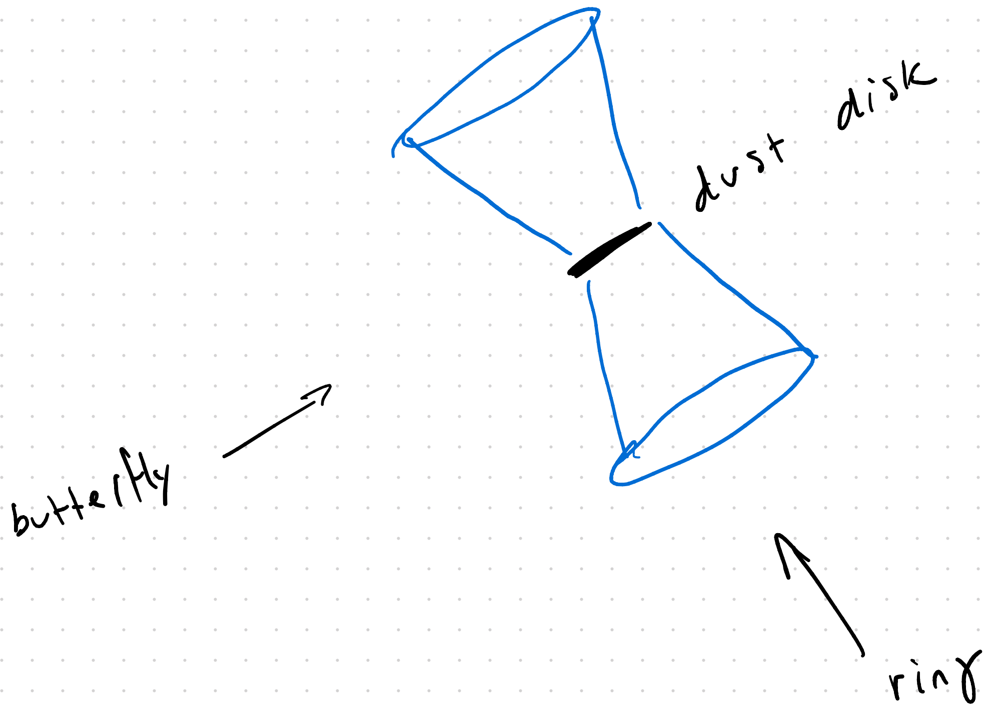


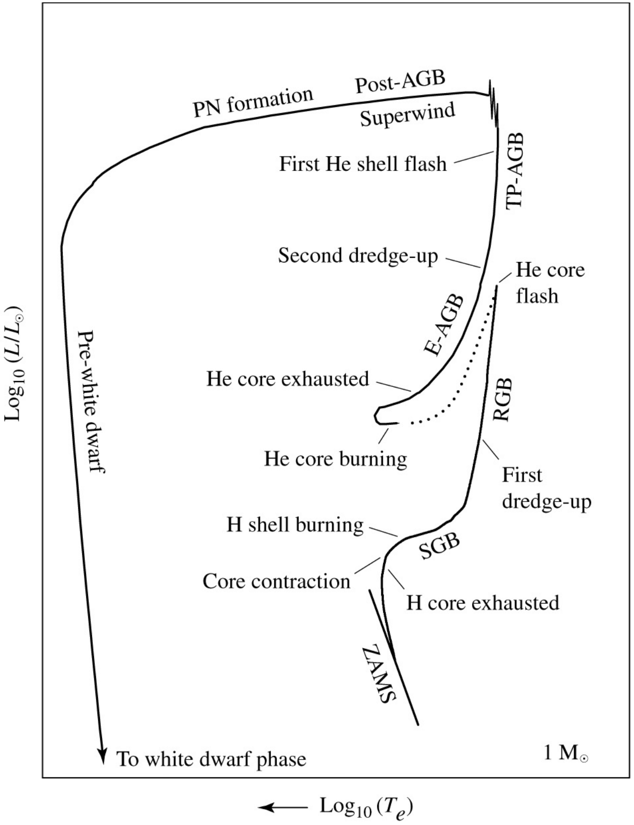


= red supergiants

lose outer layers of star to helium shell flashes




dust disk
butterfly
ring



Post-AGB
PN formation
Superwind
First He shell flash
TP-AGB
Second dredge-up
He core
flash
E-AGB
He core exhausted
RGB
He core burning
First
dredge-up
H shell burning
SGB
Core contraction
H core exhausted
ZAMS
Pre-white dwarf
To white dwarf phase
1 M$_\odot$
$\mathrm{Log}_{10}(L/L_\odot)$
← $\mathrm{Log}_{10}(T_e)$

HW 4/5 Due Monday 11/15

15.3 Mean Molecular Weights

See Ch. 14.1 Eq. 14.9

$$\mu = \left(2X + \frac{3}{4}Y + \frac{1}{2}Z\right)^{-1}$$

Mass $M_{\odot}$	MS Lifetime yrs
1	10 billion
1.5	1.5 billion
3	250 million
5	70 million
9	20 million
15	10 million
100	10,000

why do high mass stars have such short MS lifetimes?

increased mass

→ increased P, T, ρ, fusion rate

CNO cycle

carbon, nitrogen, oxygen

$$E_{CNO} \sim T^{20}$$

$$E_{pp} \sim T^{4}$$

CNO

$$^{12}C + {}^{1}H \Rightarrow {}^{13}N + \gamma$$

$$^{13}N \longrightarrow {}^{13}C + e^{+} + \nu_e$$

$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$

$$^{15}O \longrightarrow {}^{15}N + e^{+} + \nu_e$$

$$^{15}N + {}^{1}H \Rightarrow {}^{12}C + {}^{4}He$$

$$4\,{}^{1}H \rightarrow {}^{4}He$$

still do p-p chain in background

8 $M_\odot$ and up!

Carbon burning 600 million K

$$^{12}C + {}^{12}C \Rightarrow {}^{16}O + {}^{4}He + {}^{4}He$$

$$^{20}Ne + {}^{4}He$$

$$^{23}Na + p^{+} = {}^{1}H$$

$$^{23}Mg + n$$

$$^{24}Mg + \gamma$$

oxygen burning

$$^{16}O + {}^{16}O \Rightarrow {}^{24}Mg + {}^{4}He + {}^{4}He$$

$$^{28}Si + {}^{4}He$$

$$^{31}P + {}^{1}H \; (p^{+})$$

$$^{31}S + n$$

$$^{32}S + \gamma$$

1 billion K

Silicon burning

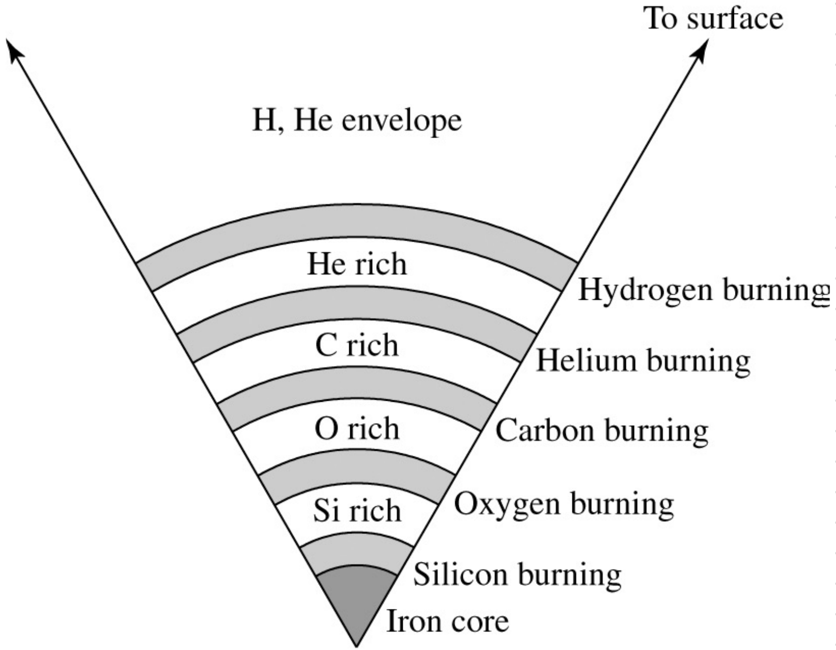
$$^{28}Si + ^{28}Si \rightarrow ^{56}Fe$$

3.5 billion K

Iron cannot be fused into heavier elements!

why is that a problem?

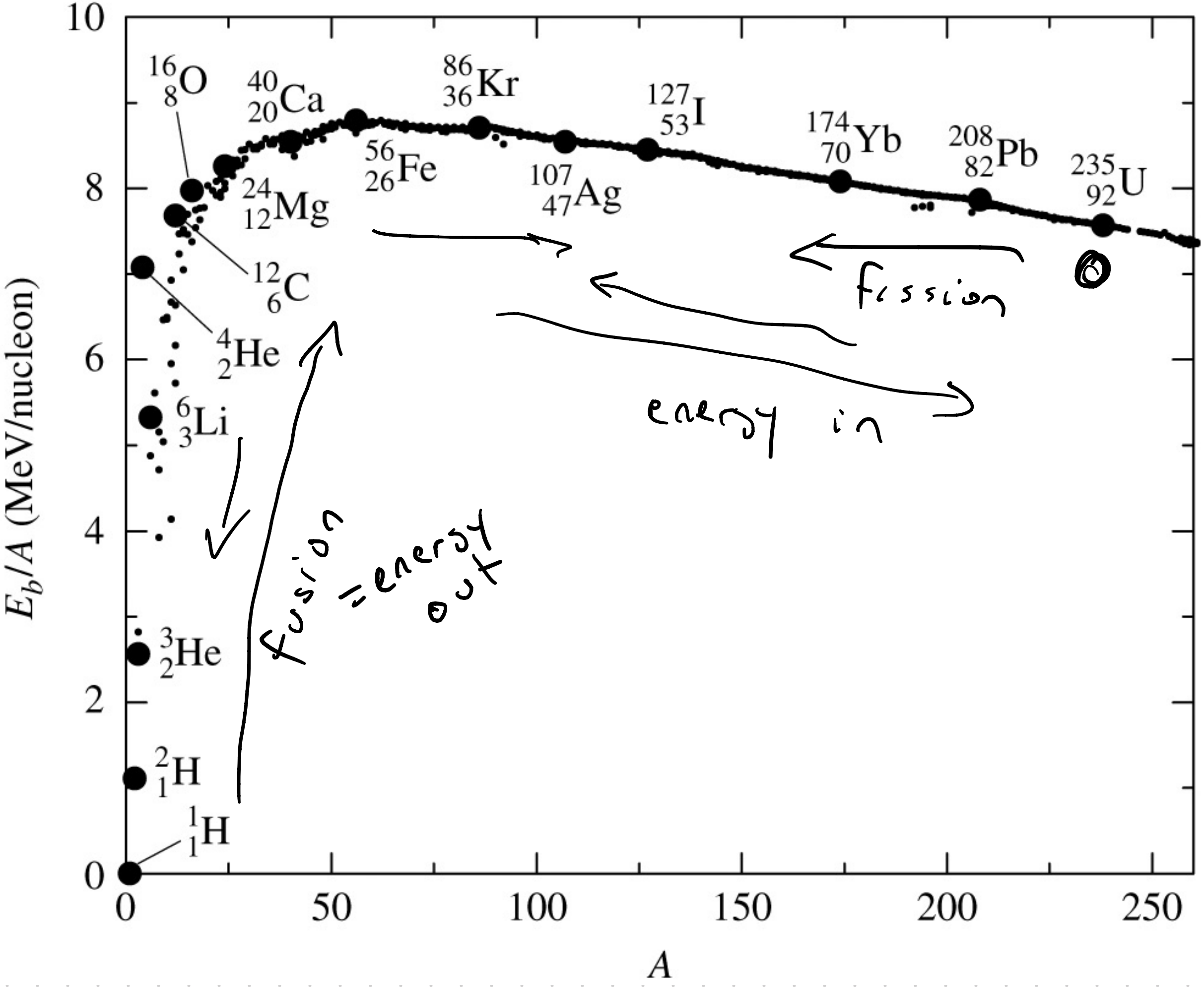
$15 M_\odot$	H	10 Myr
	He	1 Myr
	C	300 yr
	O	200 days
	Si	2 days



Supported by degeneracy pressure

$T \sim 8$ billion K

$\rho \sim 10^{10}\ g/cm^3$



binding energy

photodissociate

$$56 + \gamma \rightarrow 13\ {}^{4}He + 4n$$

$${}^{4}He + \gamma \rightarrow {}^{2}p + 2n$$

$$p^{+} + e^{-} \rightarrow n + \nu_e$$

core collapses

Earth sized core → 50 km

1 second

at 10^{15} g/cm3

collapse stops w/ neutron degeneracy pressure

bounces off

star explodes

Supernova

10^9 Lsun @ peak brightness

100×10^9 Lsun in neutrinos

Neutron capture reactions

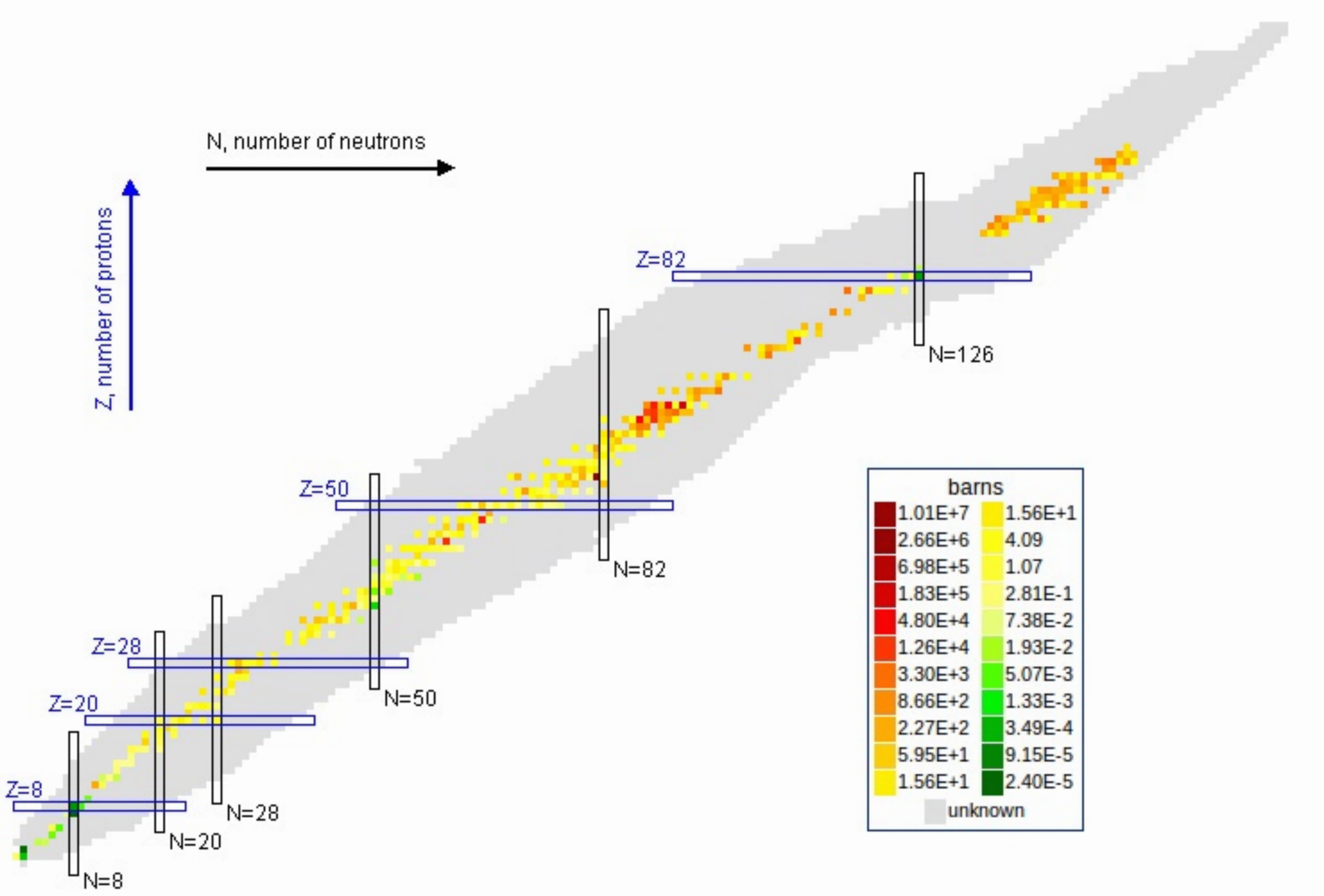
s^low-process

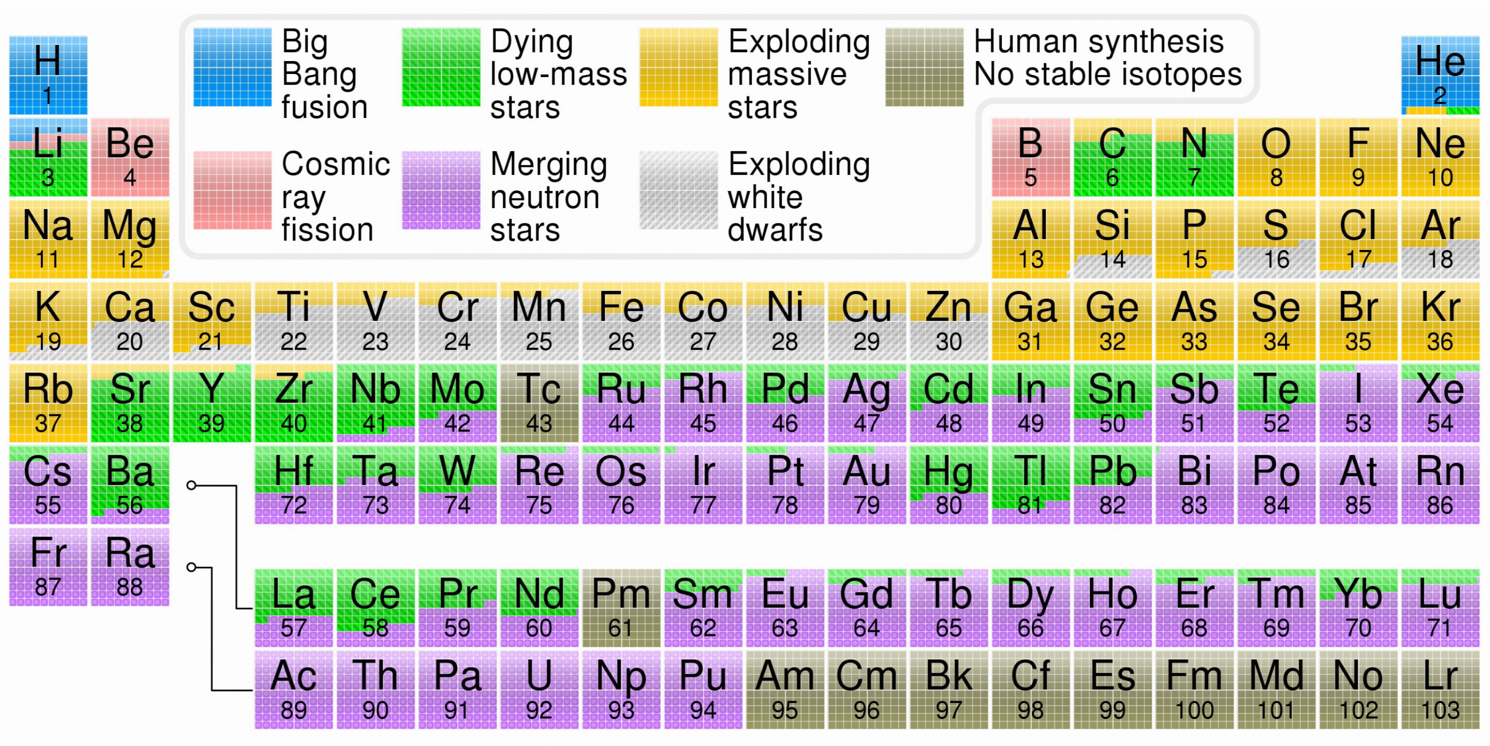
rapid-process

$$ {}^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X + \gamma $$

beta decay

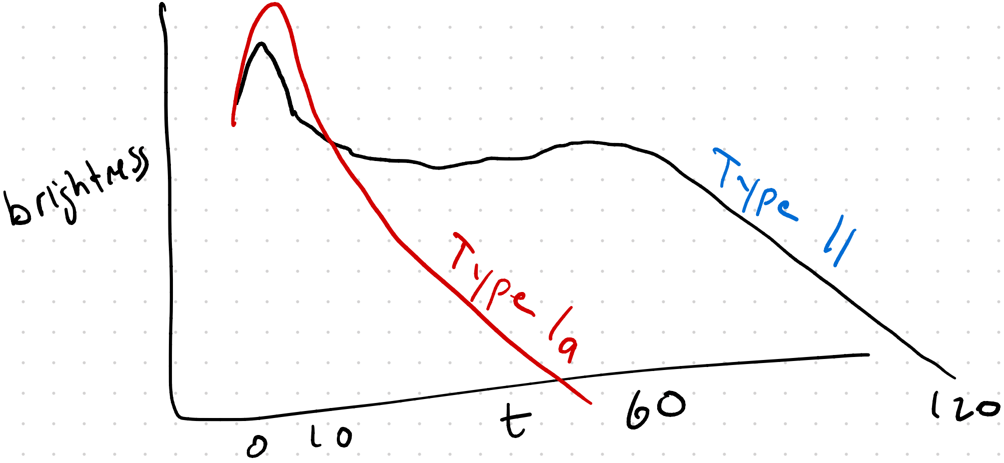
$$ {}^{A+1}_{Z}X \rightarrow {}^{A+1}_{Z+1}X + e^{-} + \nu_e + \gamma $$


N, number of neutrons
Z, number of protons
Z=82
N=126
Z=50
N=82
Z=28
N=50
Z=20
N=28
Z=8
N=20
N=8
barns
1.01E+7
2.66E+6
6.98E+5
1.83E+5
4.80E+4
1.26E+4
3.30E+3
8.66E+2
2.27E+2
5.95E+1
1.56E+1
1.56E+1
4.09
1.07
2.81E-1
7.38E-2
1.93E-2
5.07E-3
1.33E-3
3.49E-4
9.15E-5
2.40E-5
unknown


Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

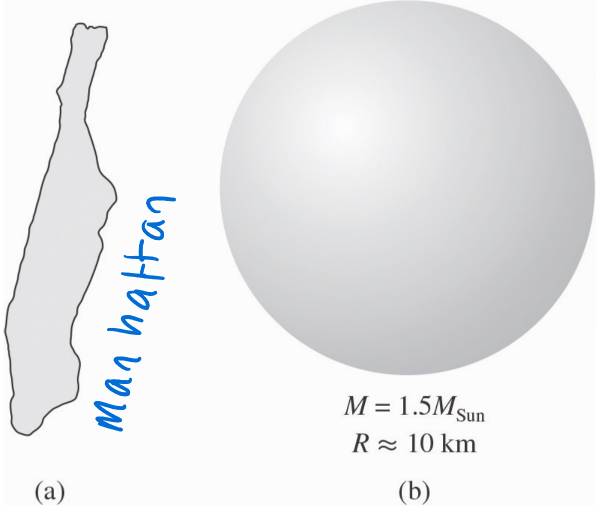
$^{56}_{28}\mathrm{Ni} \rightarrow {}^{56}_{27}\mathrm{Co} + e^{+} + \nu_e + \gamma$ 6.1 days

$^{56}_{27}\mathrm{Co} \rightarrow {}^{56}_{26}\mathrm{Fe} + e^{+} + \nu_e + \gamma$ 77.7 days



Neutron Star

mass	~1.5 - 3	$M_\odot$
radius	10 - 15	km
density	6×10^{14}	g/cm^3
v_{esc}	~0.6 c	

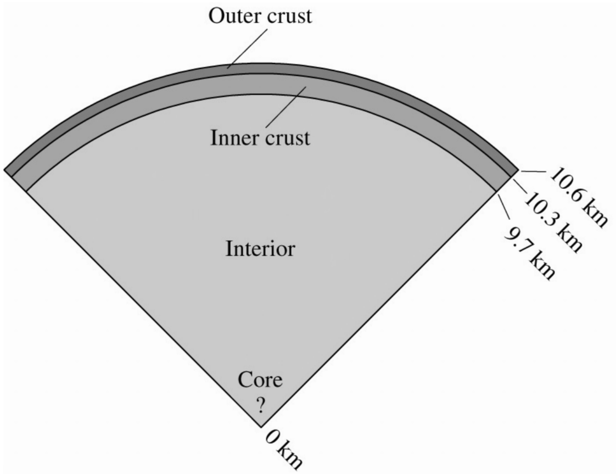


outer crust

Fe, neutron rich isotopes, electrons

inner crust

elements, neutron superfluid



Magnetic field

$B_{Earth} = 0.5$ Gauss

$B_{sun} = 1-10$ Gauss

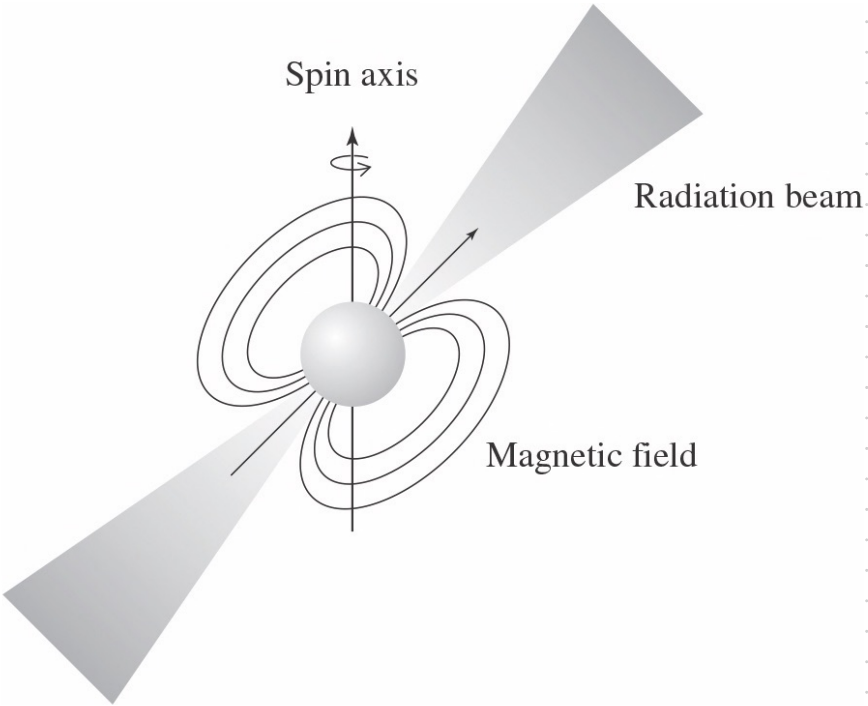
$B_{NS} = 10^{14}$ Gauss

Temp ~ 10^{11} K → 10^{6} K

Synchrotron radiation

acceleration of charged particles around magnetic field lines

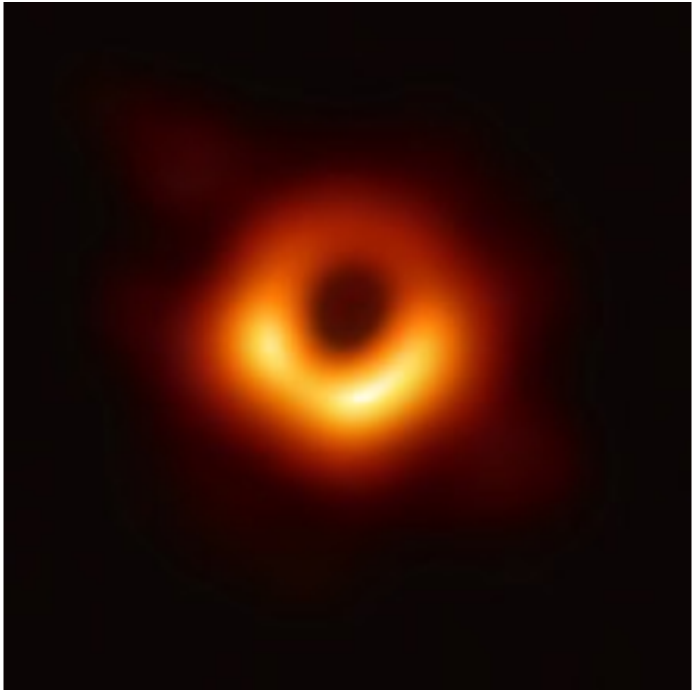
Blackbody curve peaks in X-ray



Pulsars

periods 0.25 - 2 second

Black Holes



Mass 3 - 10 M_{sun}

Spin

electric charge

"size"

$$v_{esc}^2 = \frac{2GM}{R} = c^2$$

$$R = \frac{2GM}{c^2}$$

Schwarzschild Radius

White Dwarfs

leftover cores of Sun-like stars

C & O , He

$M \simeq 1 M_{sun}$

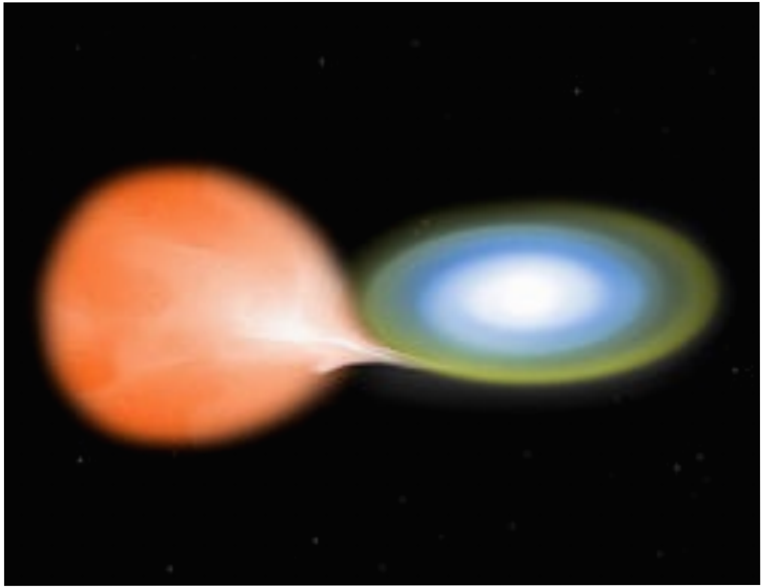
$L \simeq 0.03 L_{sun}$ $L = 4\pi R^2 \sigma T^4$

$T \sim 27,000$ K

$R \sim 0.008 R_{sun} \sim R_{Earth}$

$\rho \sim 3 \times 10^6$ g/cm^3

Maximum mass $\simeq 1.44 M_{\odot}$ Chandrasekhar Limit



Nova

material in accretion disk undergoes spontaneous $H \to He$ fusion

recurrent nova

1.3 Msun carbon burning → Fe → boom!

$L > 10^9 L_{sun}$

thermal runaway supernova

Interstellar Medium

"stuff between the stars"

hydrogen 75%

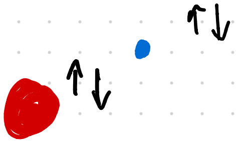
helium ~24%

molecular gases
dust > ~1%

neutral hydrogen	(H I)	100's of Kelvin	
ionized hydrogen tracer for recent star formation	(H II)	1000's of K	Balmer line emission spectra
molecular hydrogen	(H_2)	10's of K	

neutral hydrogen

mostly in ground state



true ground state is up/down

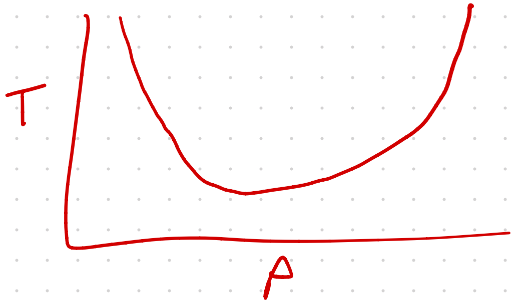
up/up or down/down have a little extra energy

$$E = \frac{hc}{\lambda}$$

$$\Delta E = 6\times10^{-6} \text{ eV}$$

$$\lambda = 21 \text{ cm}$$ (radio)

Molecular Hydrogen



CO (2.6 mm) emits at 2.6 mm

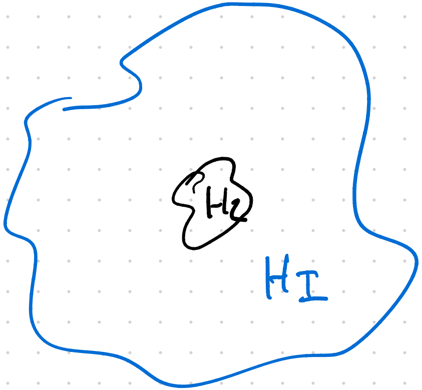
dust

HCN

NH_3

"molecular clouds"

	HI cloud	molecular cloud core
Temp	50 K	150 K
Density	500 #/cm^3	$10^?$ #/cm^3
Mass	1-100 $M_\odot$	10 - 1000 $M_\odot$



Virial Theorem

$$K + U = 0 \qquad E = 1/2\, U$$

$$K = 1/2\, U$$

$$N = \frac{M}{m} \quad \frac{\text{total}}{\text{particle mass}}$$

$$K = N\left(3/2\, kT\right)$$

$$R = \left(\frac{3N}{4\pi\rho}\right)^{1/3}$$

$$U = -\frac{3}{5}\frac{Gm^2}{R}$$

$$3NkT < \frac{3}{5}\frac{Gm^2}{R}$$

$$M > \left(\frac{5kT}{Gm_{\text{particle}}}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$$

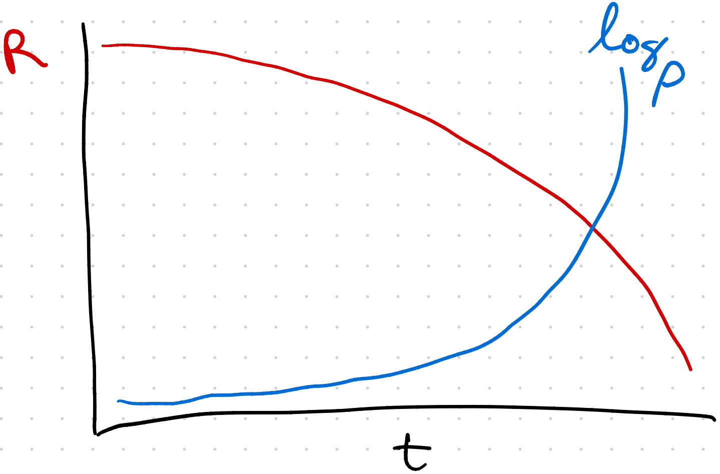
Jeans mass

when you exceed limit

(part) of the cloud can collapse

Isothermal collapse = "same temperature"

cloud is optically thin, heat radiates away



free-fall time

$$a = \frac{GM(r)}{r^2} \qquad r = \frac{1}{2} a t_{ff}^2$$

$$= \frac{4}{3}\pi G r \rho$$

$$t_{ff} \sim \sqrt{\frac{1}{G\rho}}$$

$t_{ff} = \sqrt{\frac{1}{G\rho}}$ $M \sim \sqrt{\frac{1}{\rho}}$

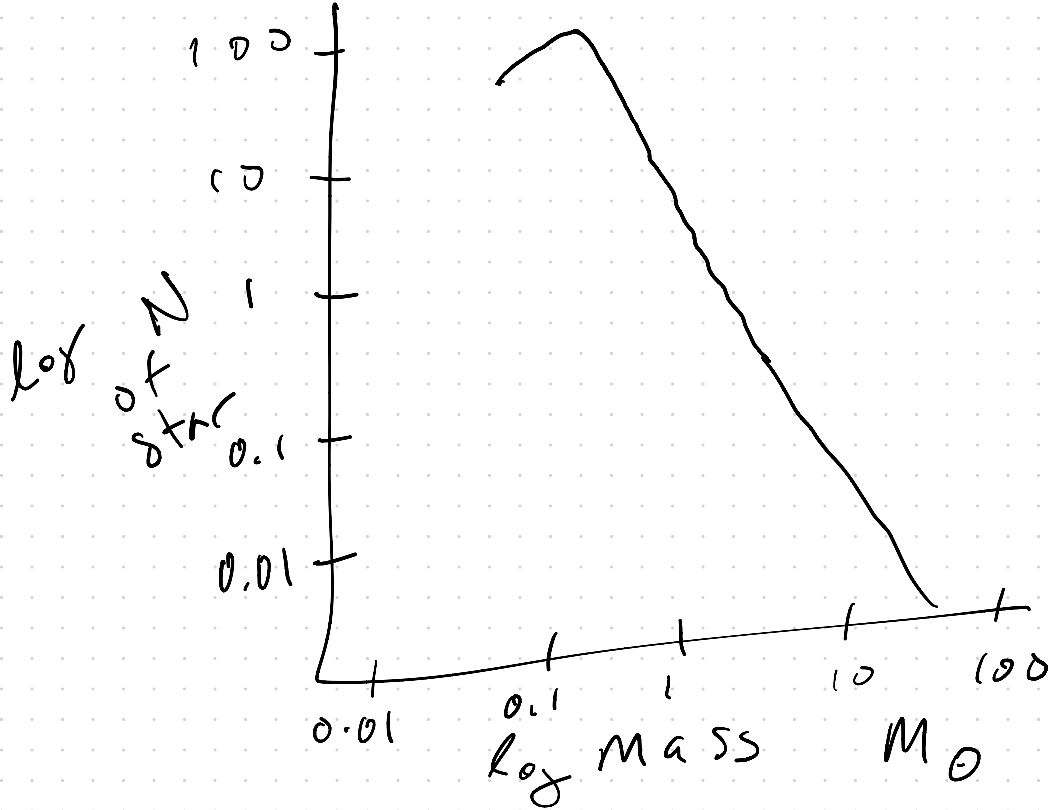
Fragmenting big cloud into smaller pieces that each collapse independently into a star

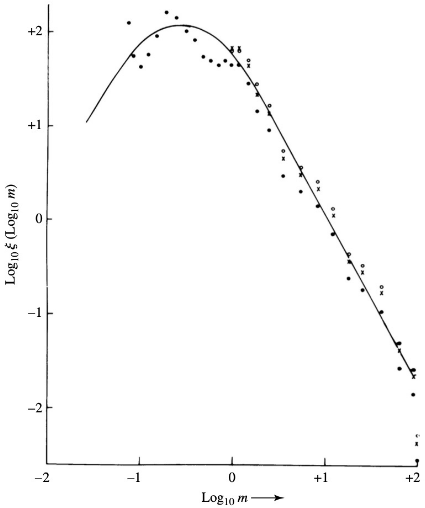
smallest clump $\sim 1/2\, M_{\odot}$

eventually cloud is too opaque

adiabatic collapse → higher T → higher P

initial mass function





h & χ persei

h & χ Persei

M13

blue

not dense

irregular shapes

differences?

stars more red

red giants?

denser distribution

spherical

open clusters

bluer, younger stars

low densities

~1000 stars

10-100 million years old

found in areas of recent star formation

found in disks of spiral galaxies

globular clusters

cool, red stars

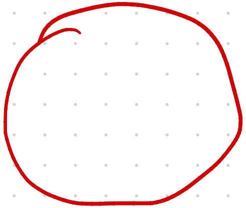
old 13-14 billion years old

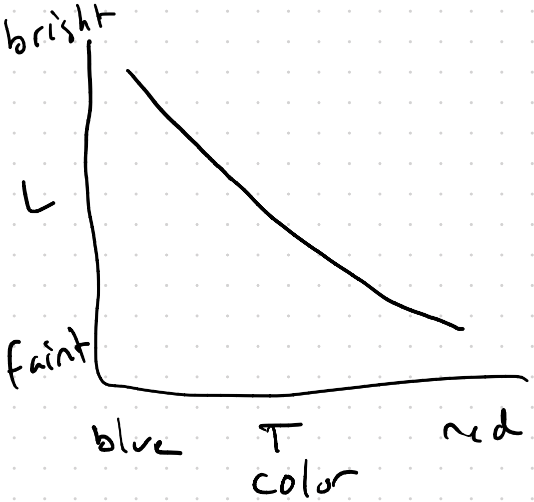
high density

100,000 stars

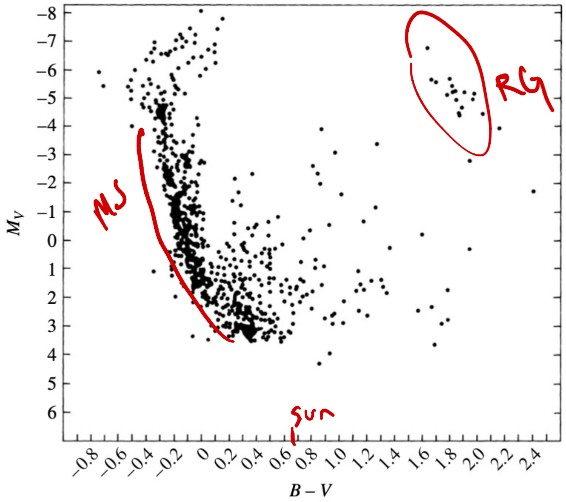
mainsequence, red giant stars

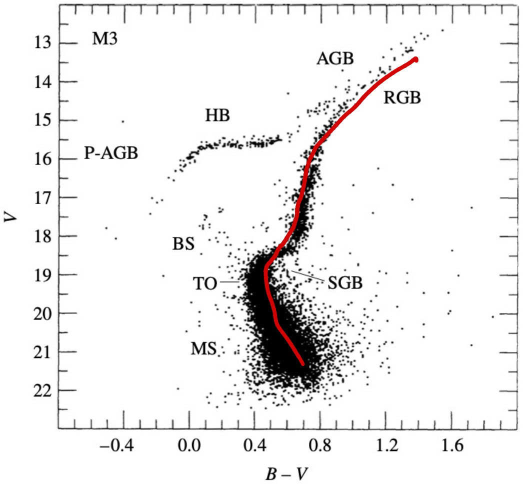
found around galaxies of all types



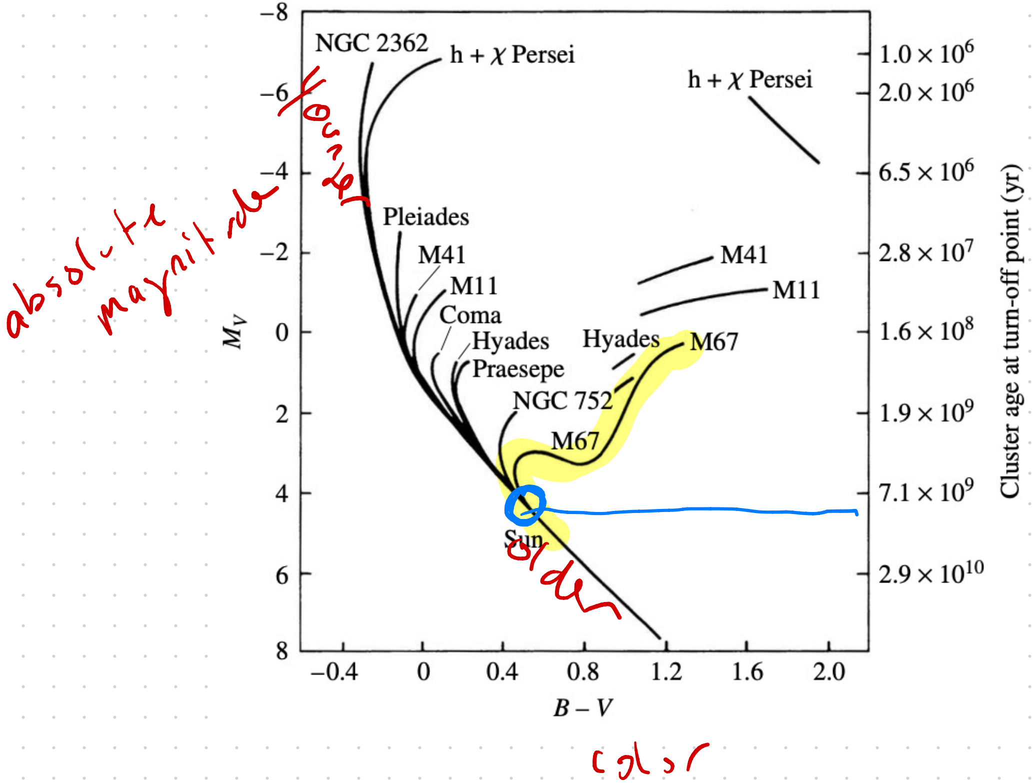

bright
L
faint
blue
T
red
color


bright
L
faint
blue
T
red
color


M_V
−8
−7
−6
−5
−4
−3
−2
−1
0
1
2
3
4
5
6
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
B − V
MS
RG
sun


M3
AGB
RGB
HB
P-AGB
BS
TO
SGB
MS
V
13
14
15
16
17
18
19
20
21
22
−0.4
0.0
0.4
0.8
1.2
1.6
B − V

isochrones = same age

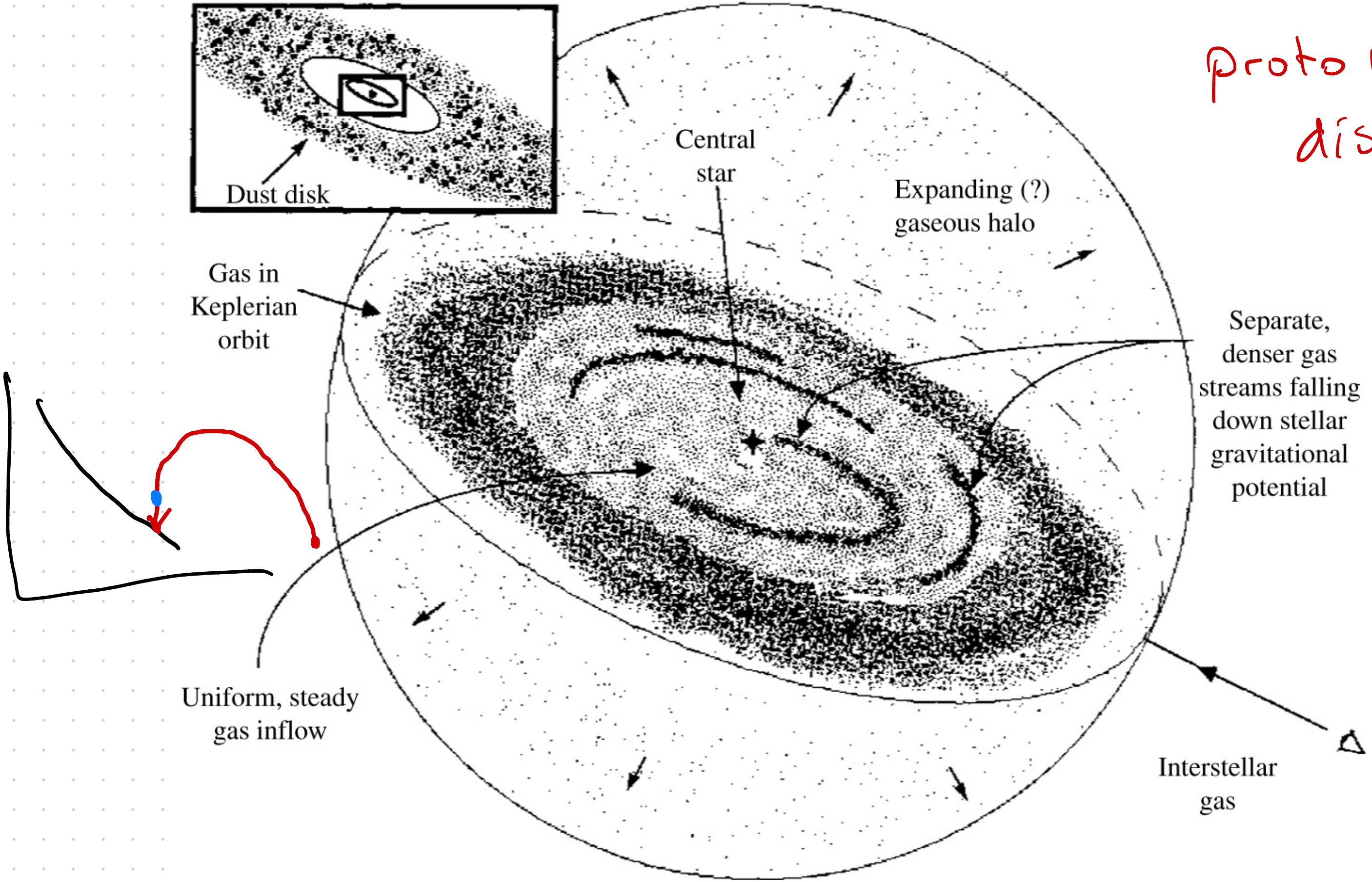


main sequence fitting

distance modulus $m - M = 5 \log_{10} d(pc) - 5$

proto
star

proto planetary disk



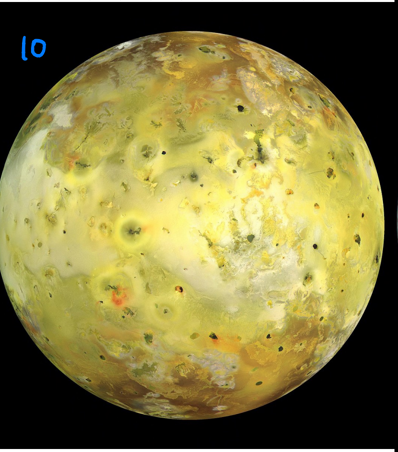
Galilean Satellites of Jupiter (1610)

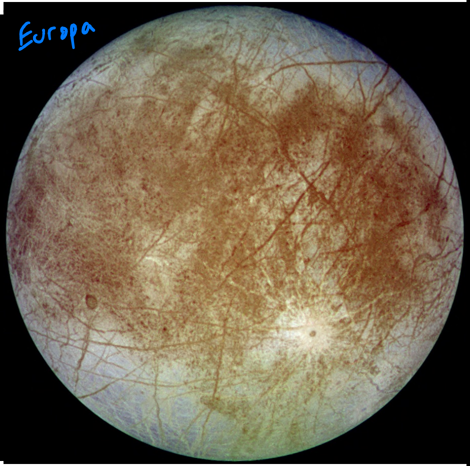
x Earth moon

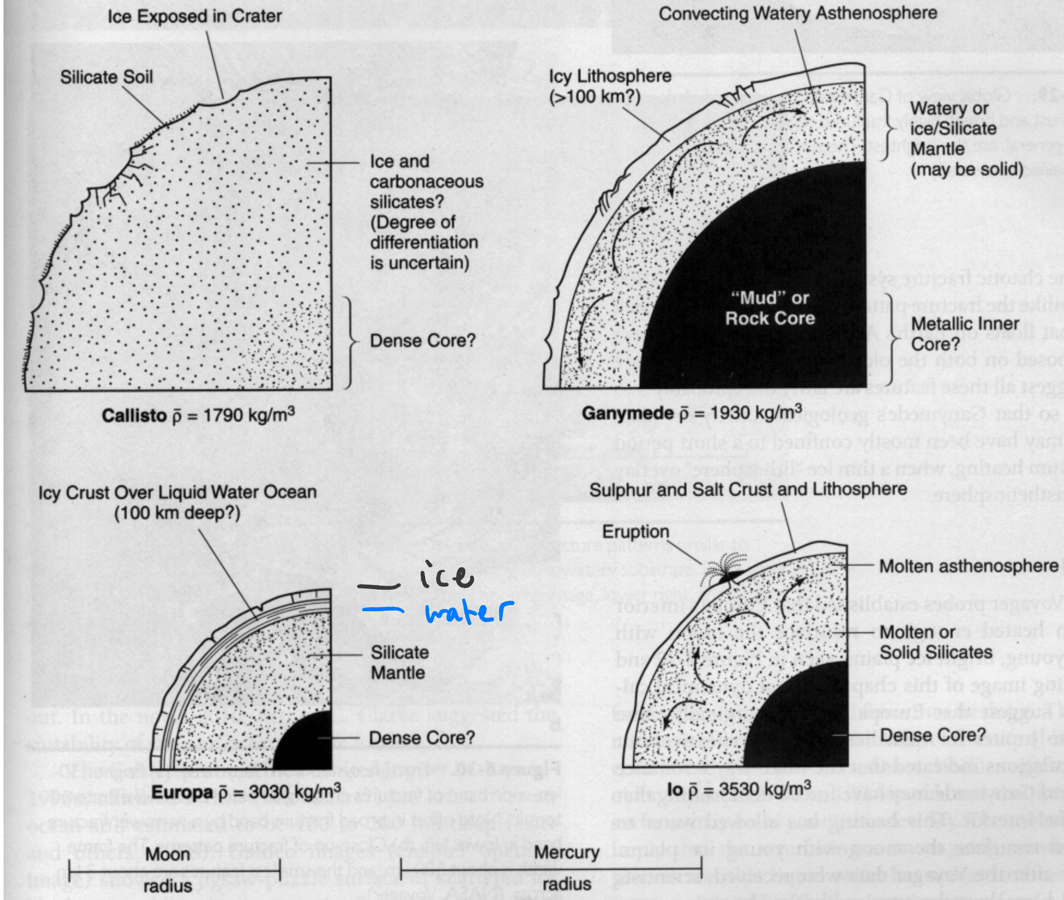
	Mass	Radius	Density
Io	1.2	1.1	3500 kg/m^3
Europa	0.65	0.9	3000
Ganymede	2.0	1.5	1900
Callisto	1.5	1.4	1800

kg/m^3

Iron	~7000
Rock	~3000
H_2O ice	~1000
$\langle \rho_{Earth} \rangle$	~5500

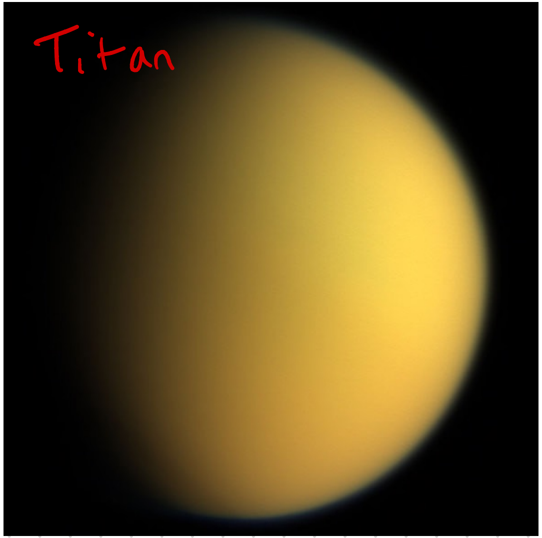






— ice
— water

Figure 8-28. Schematic models of the Galilean satellite interiors based on thermal calculations and data from Voyager and Galileo probes. (Adapted from data reviews by Torrence Johnson, plus recent references mentioned in text)



Atmosphere!

Methane

Nitrogen

Argon

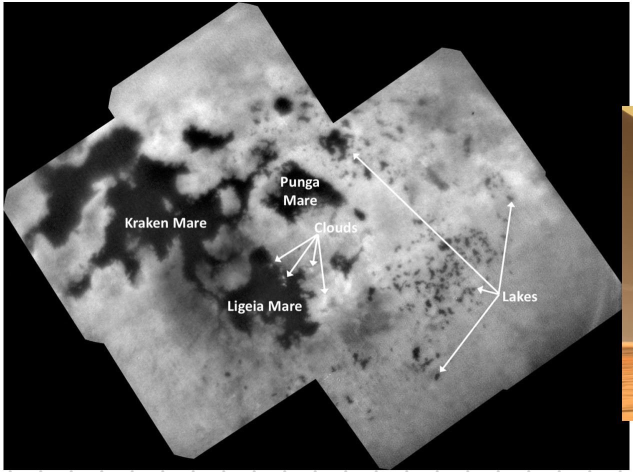
Ethane, Propane, other Organics

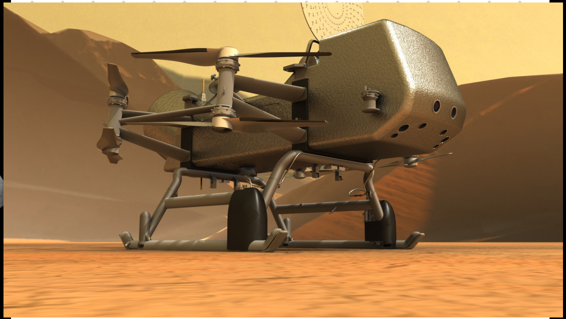
Second largest Moon

surface pressure
1.5 atm

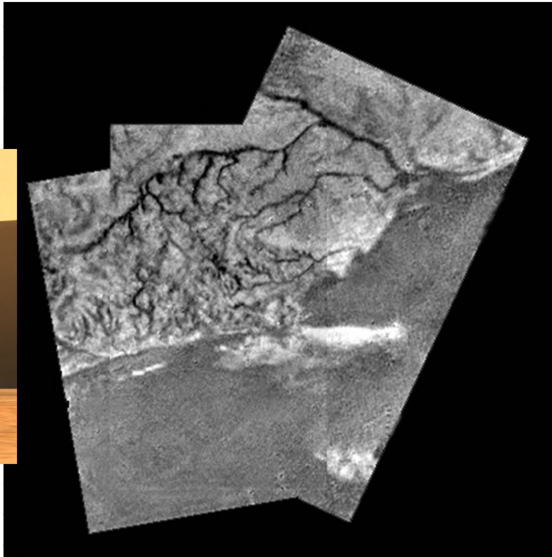
cold surface 94 K

methane triple point
= 91 K





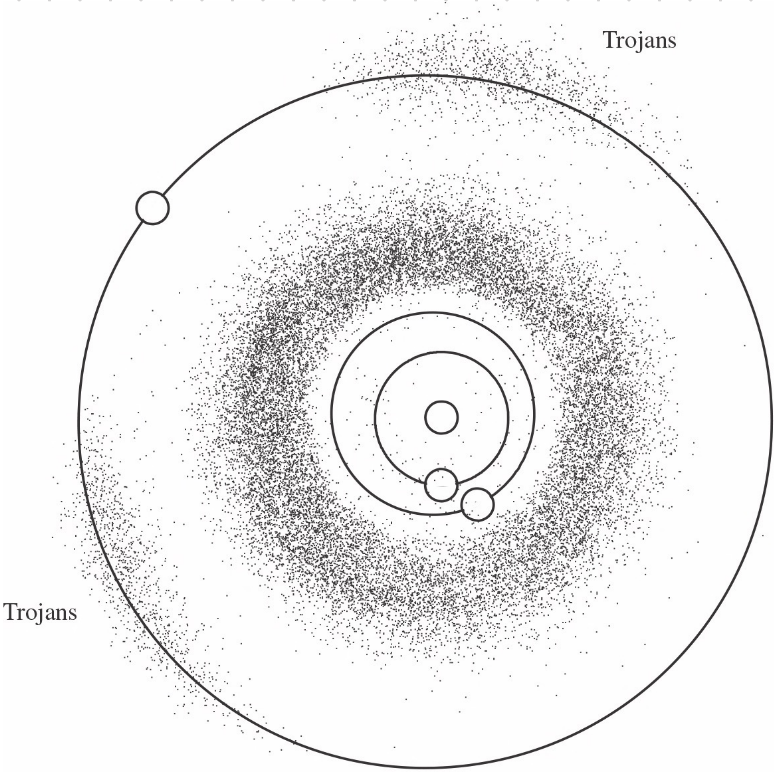
drone mission launch 2027



Asteroids

Small rocky bodies "mostly" between Jupiter & Mars

↳ Asteroid belt

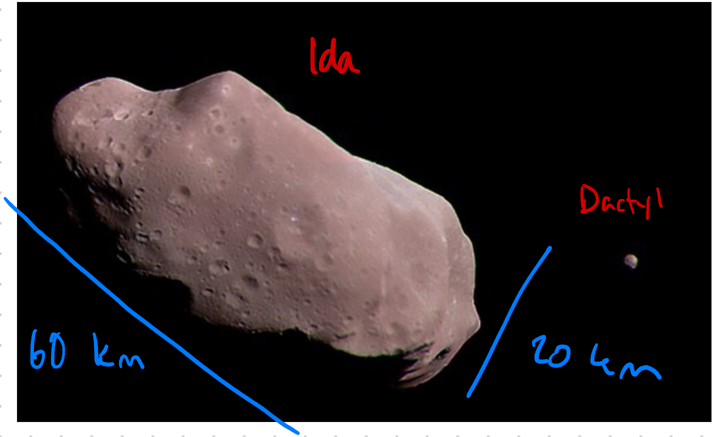


what are asteroids?

$N(R) \propto 1/R^2$ size distribution

biggest = Ceres 900 km

only 26 bigger than 200 km



material was never able to form a planet

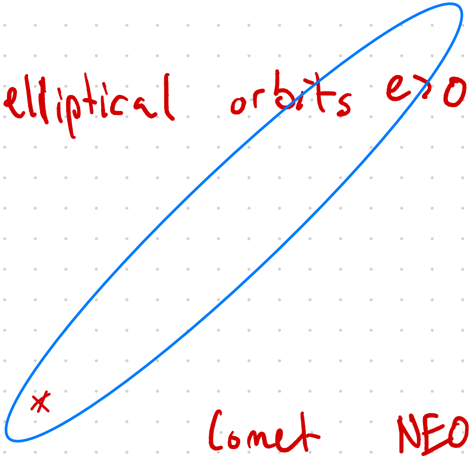
add up to less than mass of Earth's moon

10 - 30% of asteroids have moons
"satellites"

Comets

"Dirty Space Snowballs"

highly elliptical orbits $e > 0.9$



- mostly water ice
  ammonia
  silicates (dust)
  organic material

Comet NEOWISE

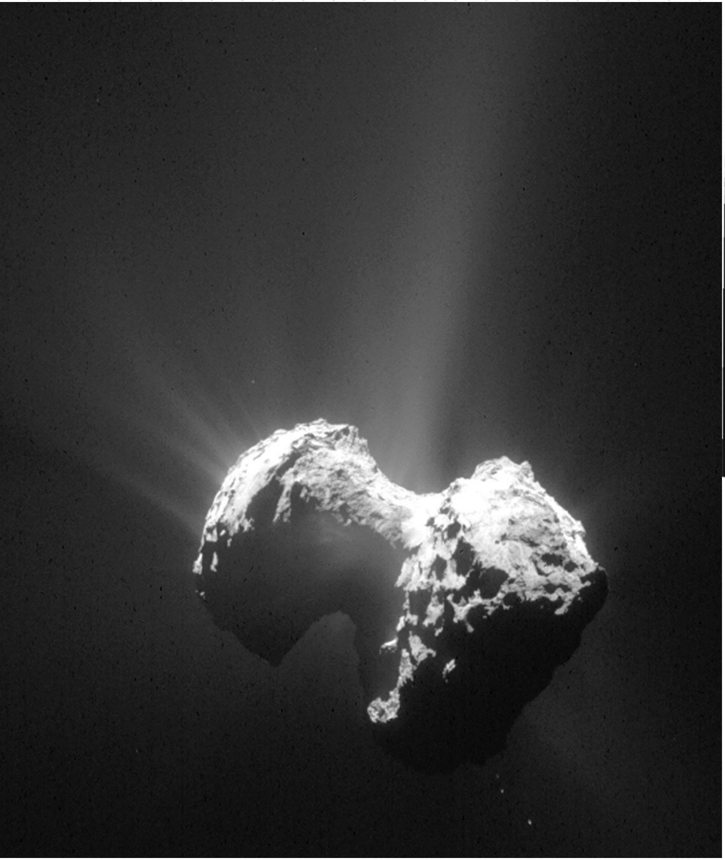
Nucleus ~ a few km

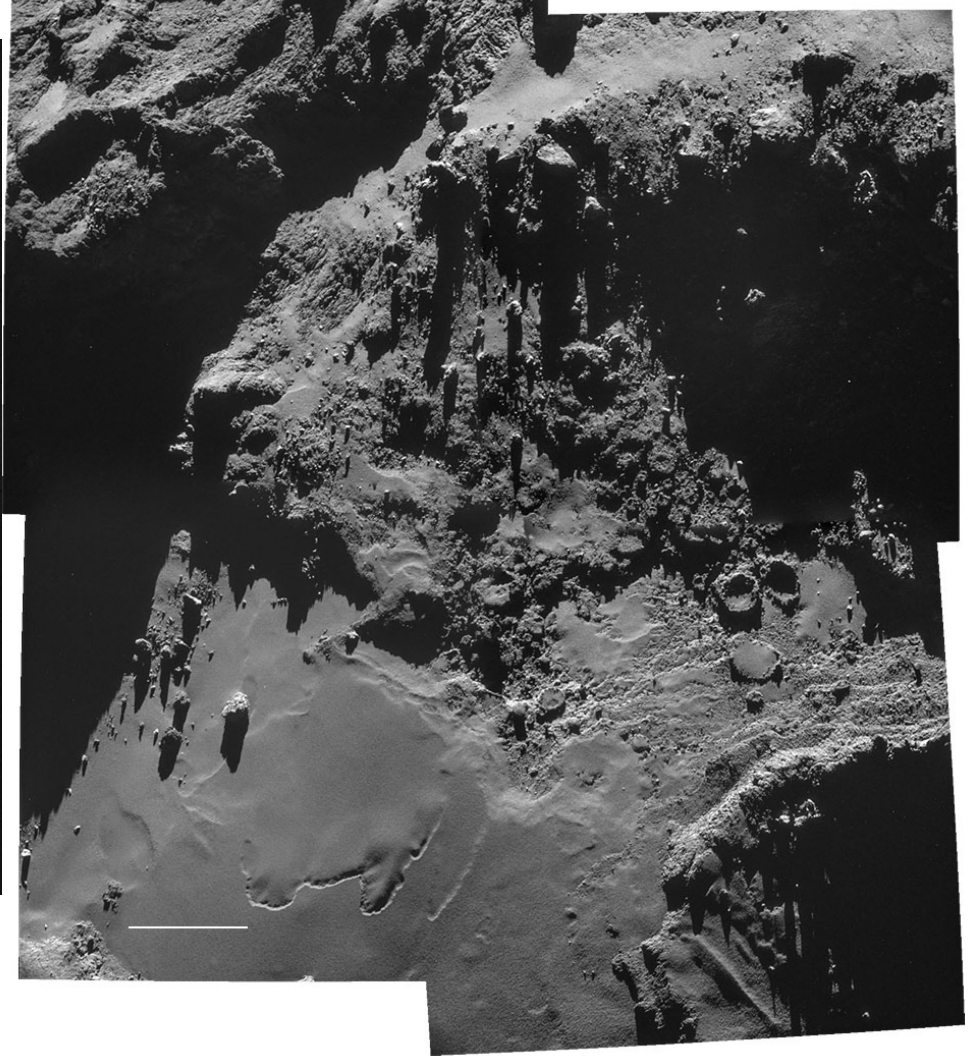
Coma heated cloud of gas/dust ~10,000 km

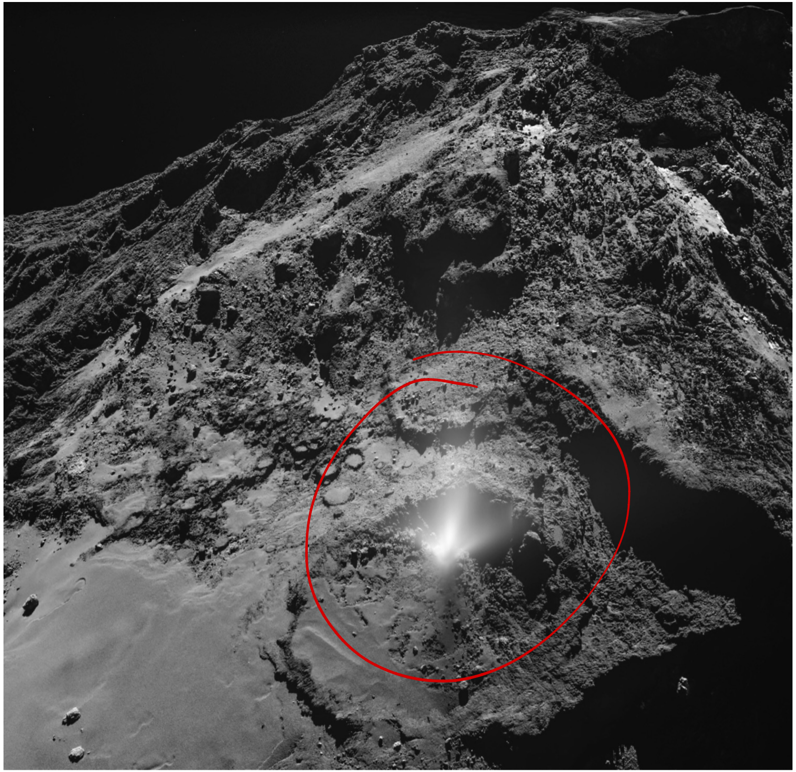
Tail ~ a few million km long

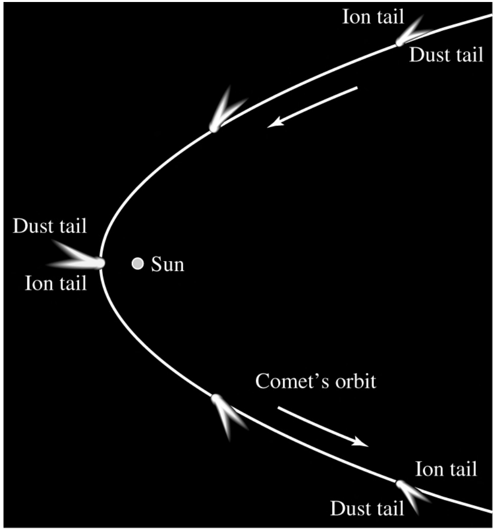
ion tail solar wind, magnetic field lines

dust tail trailing particles pushed by radiation pressure









Radiation Pressure

photons can carry momentum

$$p = \frac{E}{c}$$

$$F = \frac{dp}{dt} = \frac{1}{c}\frac{dE}{dt}$$

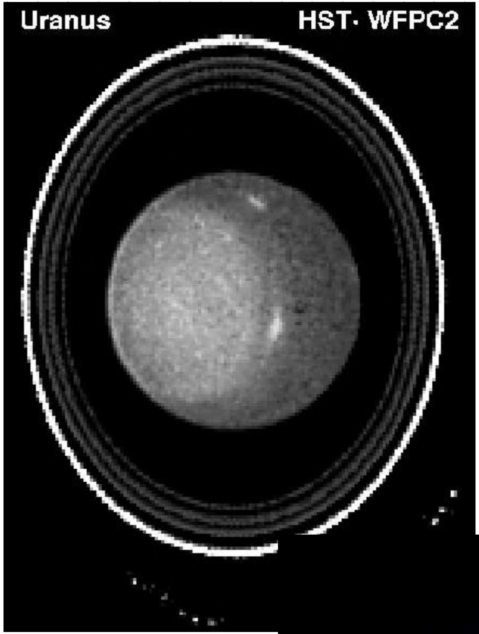
Luminosity

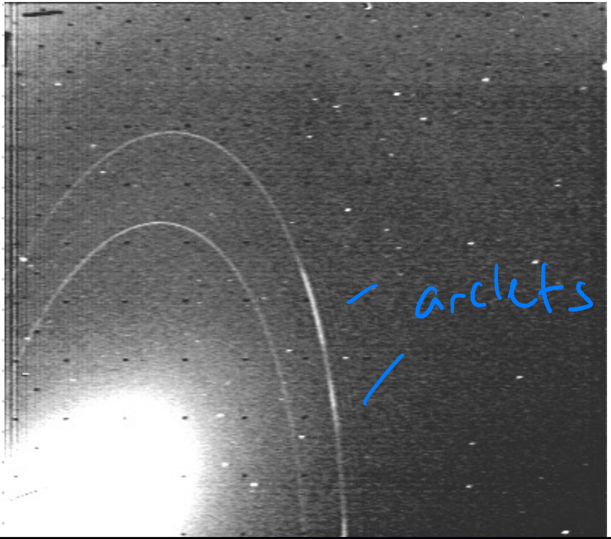
consider a shell of radius R

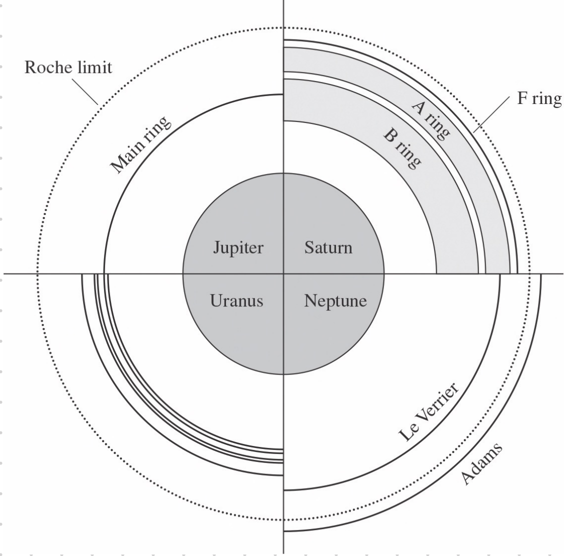
$$\text{pressure} = \text{force}/\text{area} = \frac{1}{c}\frac{dE}{dt}/4\pi R^2$$

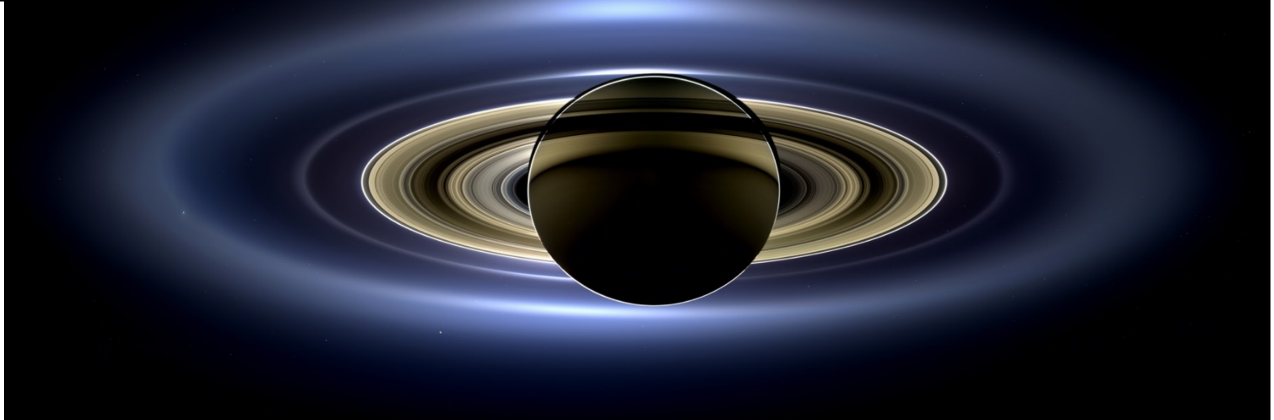
$$P_{rad} = \frac{L_\odot}{4\pi R^2 c}$$

distance from Sun

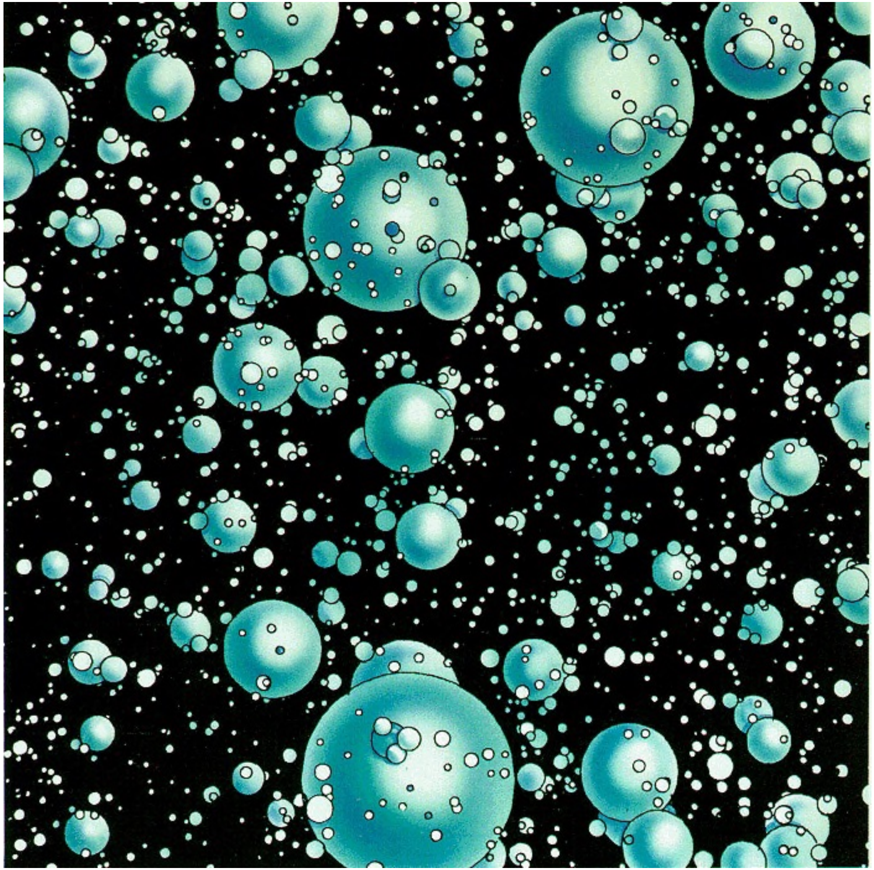

Uranus
HST· WFPC2


arclets


Roche limit
F ring
Main ring
A ring
B ring
Jupiter
Saturn
Uranus
Neptune
Le Verrier
Adams

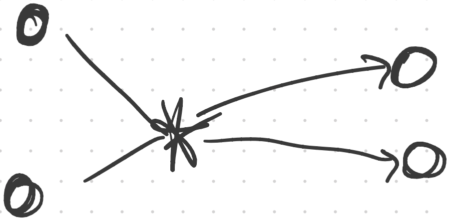


what are rings?



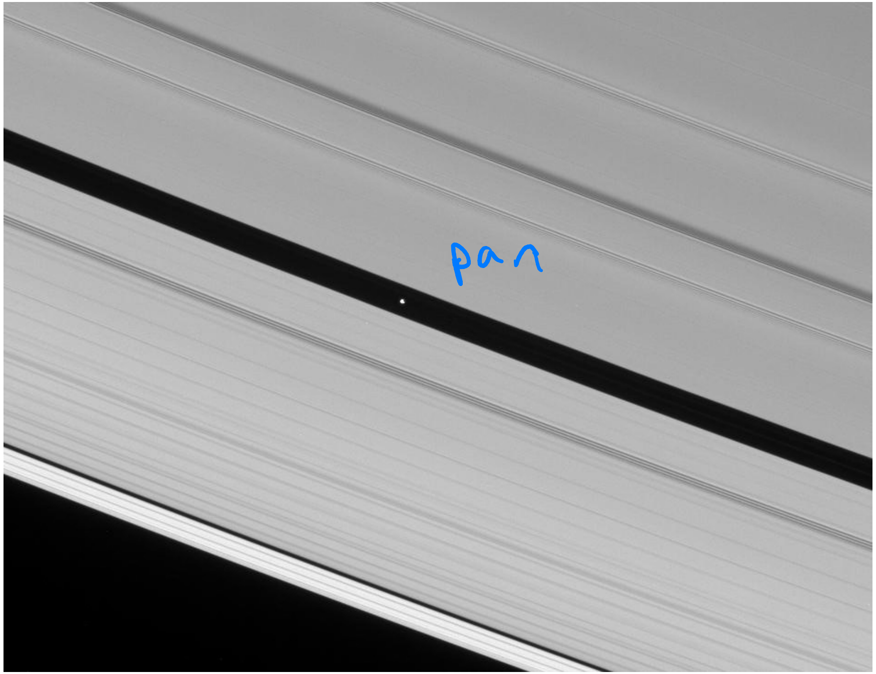
ice particles!

sizes between
1 cm & 3 m

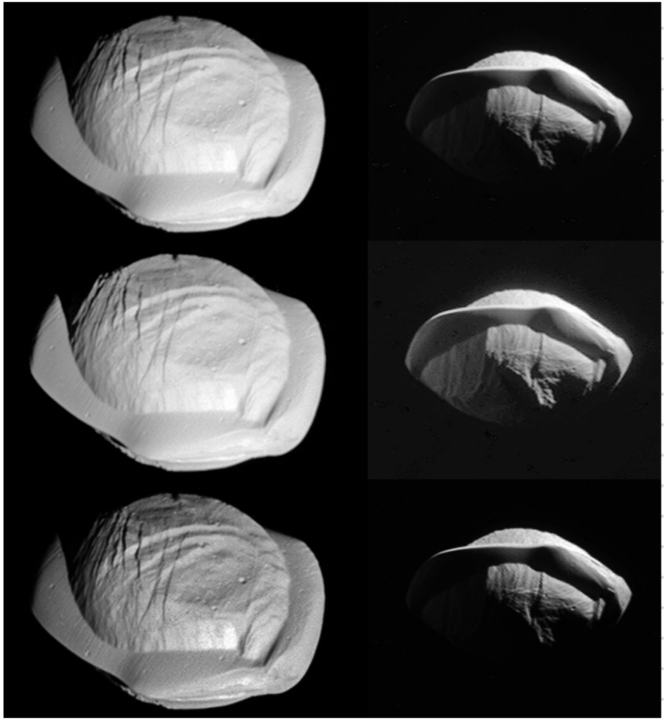


only a "few dozen" = 30 m
meters thick

gaps come from orbital
resonances, "shepherd moons"

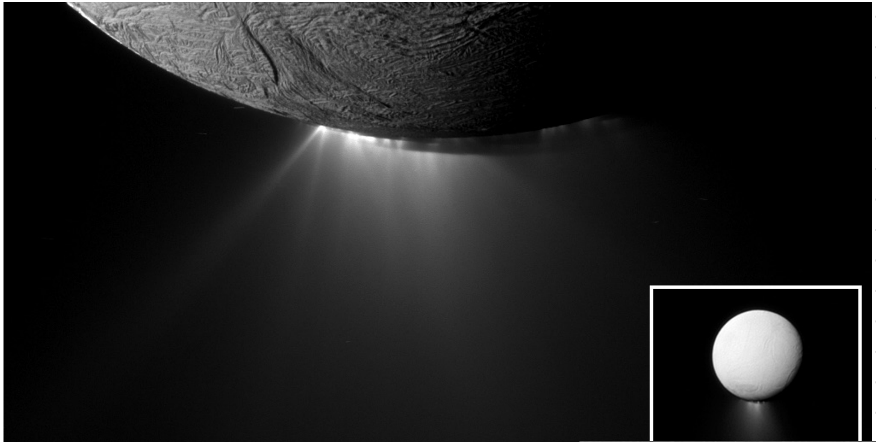


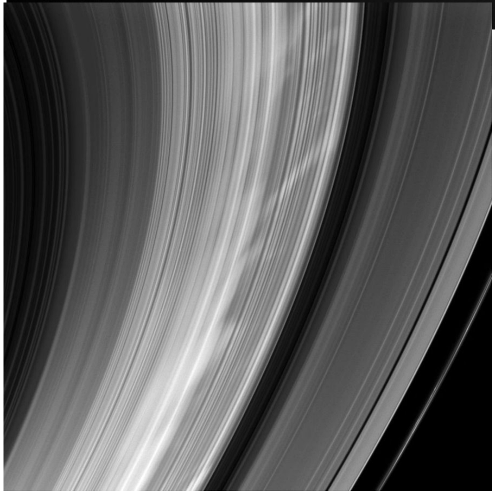
why are rings?

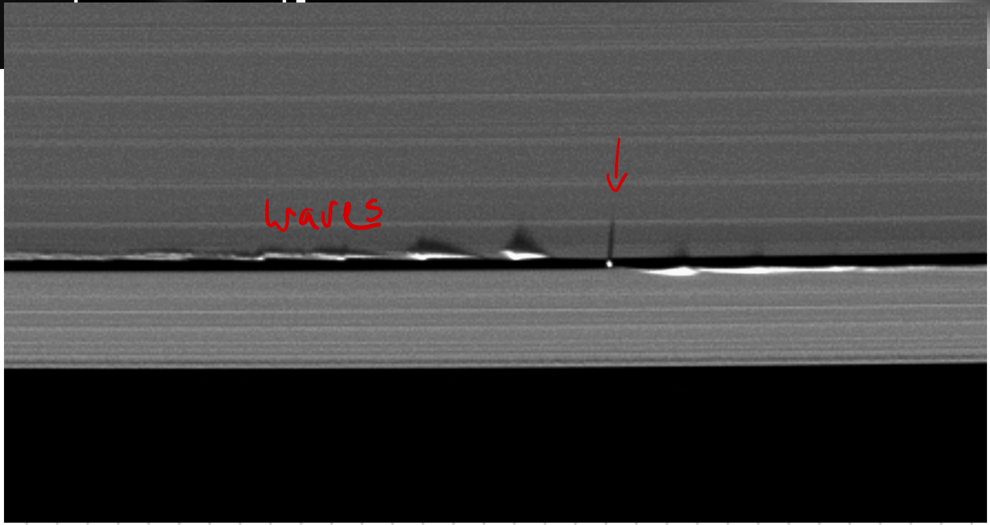


Pan up close

space ravioli






waves

Kuiper Belt Objects

outside of Neptune's orbit

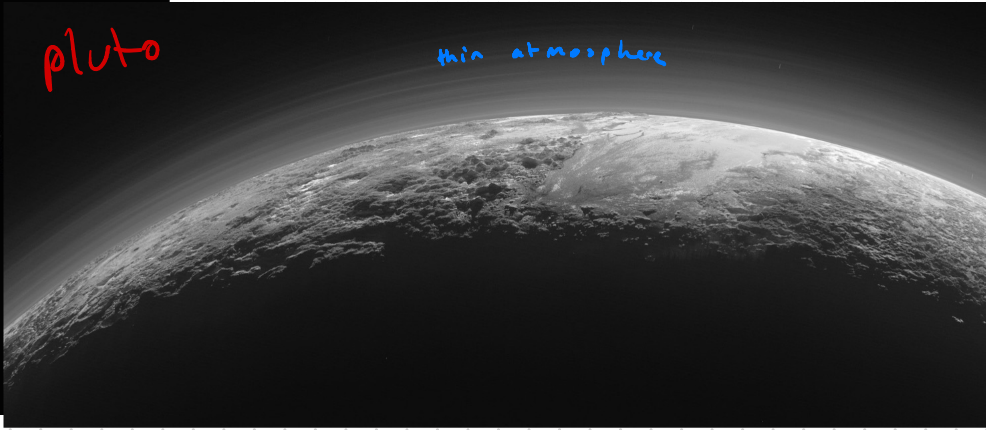
Pluto and Friends

dwarf planet

rock and ice combined

oort cloud (spherical)

source of comets



Earth's Atmosphere

% by #	
78%	N_2
21%	O_2
1%	Ar
0.04%	CO_2
trace	Ne, He, CH_4, Kr

pressure gradient follows ideal gas Law + hydrostatic equilibrium

$$P(r) = P_0 e^{-\frac{r-R_0}{H}}$$

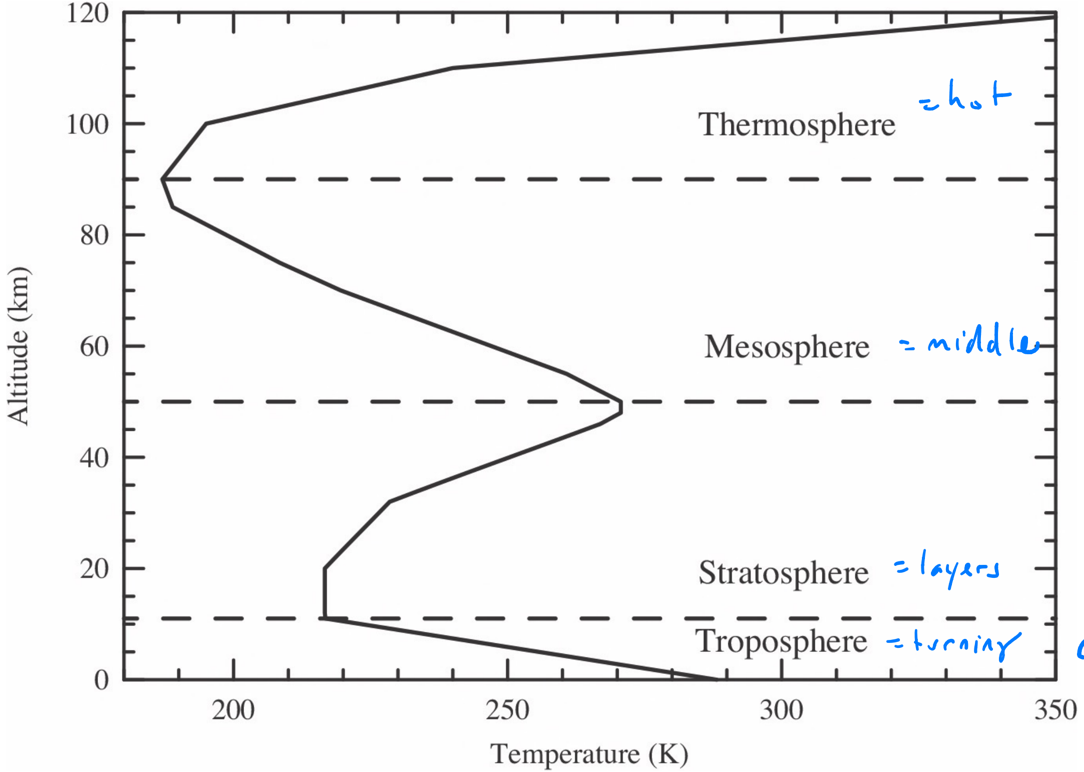
P_0 = sea level pressure = 1 atm $= 10^5 N/m^2$

R_0 = radius = 6378 km

H = scale height $= \frac{kT}{g \mu m_p}$

(ρ drops to 37%)

= 8 km ~ Mt Everest



+ ionosphere

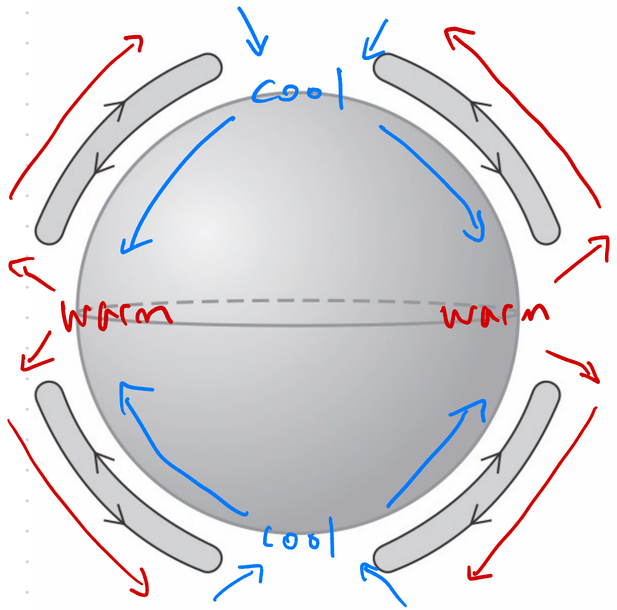
meteors burn up
not much going on

no convection = planes
contains ozone layer
absorbs UV light

convection = weather
most of material ~ 80%

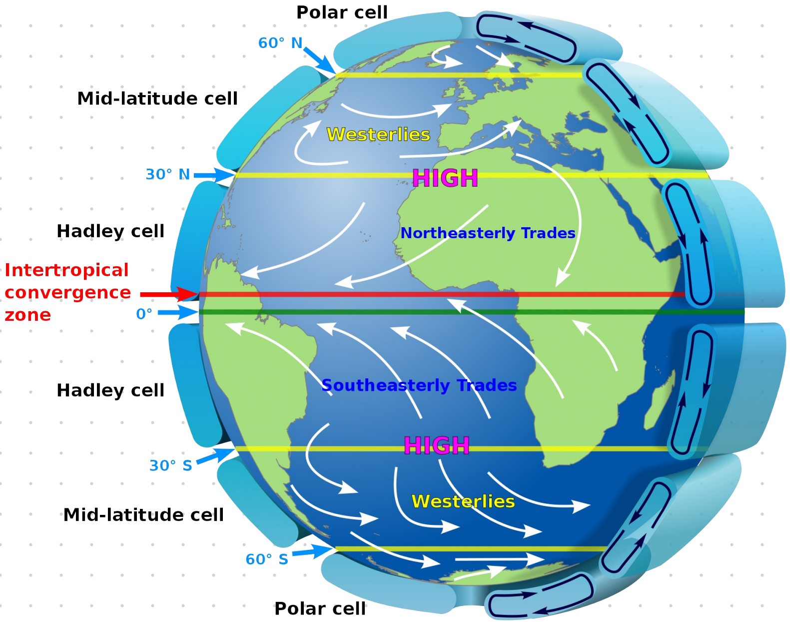
Hadley circulation

simple



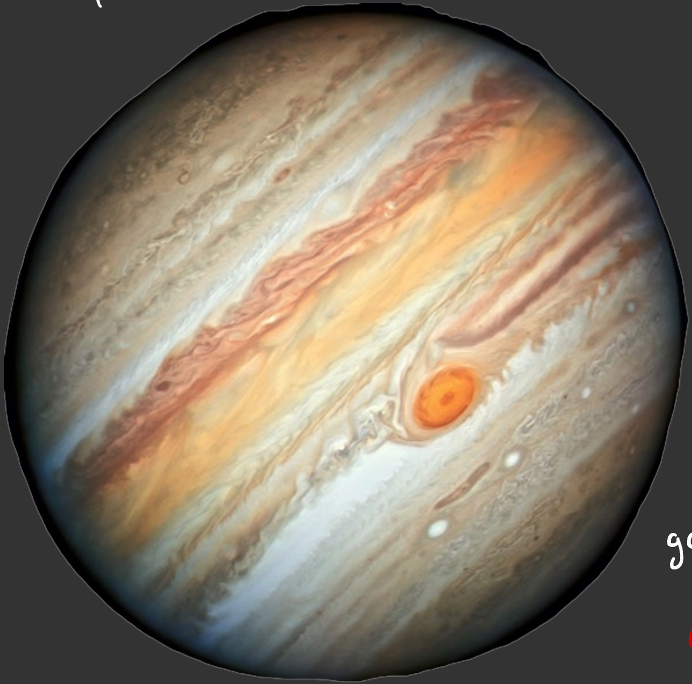
(a)

+ Coriolis effect



		Jupiter	Saturn	Uranus	Neptune
Radius	~70,000 km	1	0.85	0.36	0.35
Mass	~ 1×10^{27} kg	1	0.3	0.045	0.053
Density	$H_2O = 1,000$	1,330 kg/m^3	690 kg/m^3	1270 kg/m^3	1640 kg/m^3
Distance from Sun		5.2 AU	9.5 AU	19.2 AU	30.1 AU
T_{eq}		110 K	80 K	60 K	45 K
T_{obs}		125 K	95 K	60 K	60 K
Notes		cloud patterns faint rings 70+ moons t_{rot} = 10 hr	cloud patterns rings! 50+ moons t_{rot} = 10.6	featureless tiny rings 20+ moons t_{rot} = 17.3 hr axis tilt ~ 90°!	cloud patterns "arclets" 20+ moons t_{rot} = 19.2 hours

Jupiter



atmosphere composition

Hydrogen, Helium

Ammonia (NH_3), Methane (CH_4)

Ammonia Hydrosulfide (NH_4HS)

bright "zones" =
gas moving ↑, see cool top

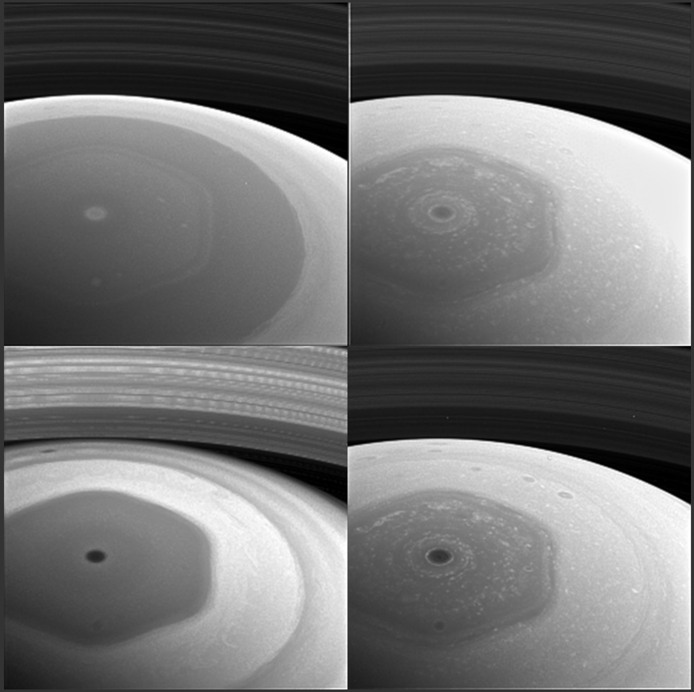
dark "bands" =
gas moving ↓, darker inner layers

Stripes = convection bands

shear between cloud bands causes cyclonic storms

Saturn

polar hexagon!

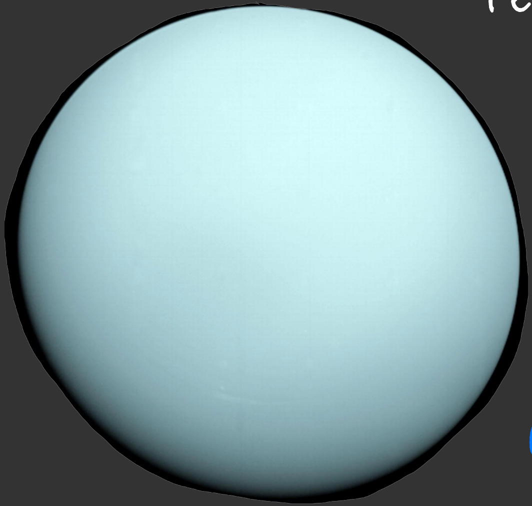


composition

H, He, methane, ammonia, water ice

video

Uranus

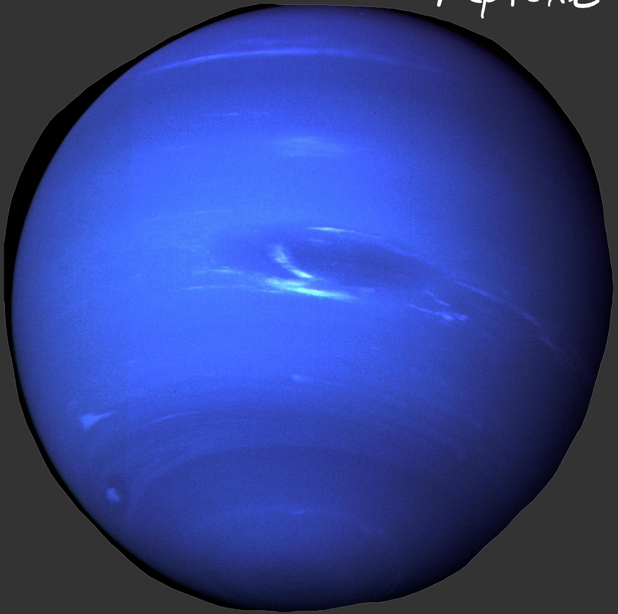


relatively featureless surface

due to lack of convection

Uranus is @ equilibrium temp!

Neptune



great dark spot

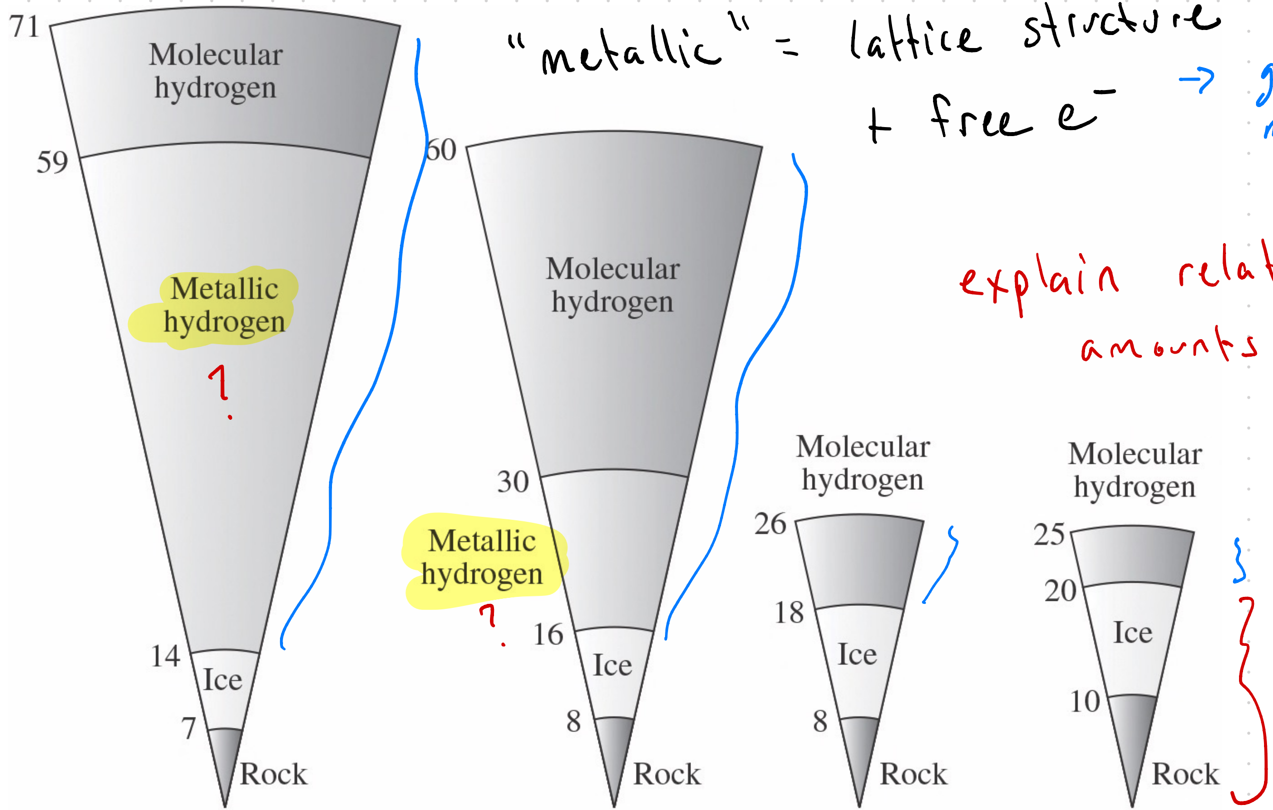
color differences due to molecular differences

T, UV light → ammonia, methane, etc

yellow blue red

interior structures

"metallic" = lattice structure + free e^- → generates magnetic field



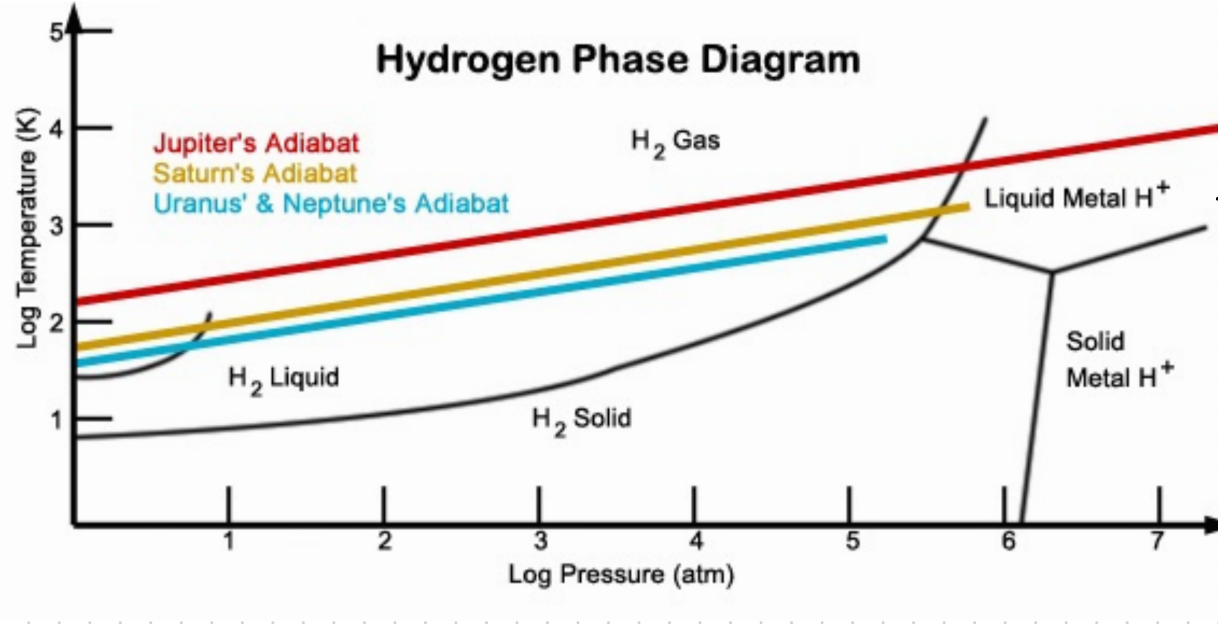
(a) Jupiter (b) Saturn (c) Uranus (d) Neptune

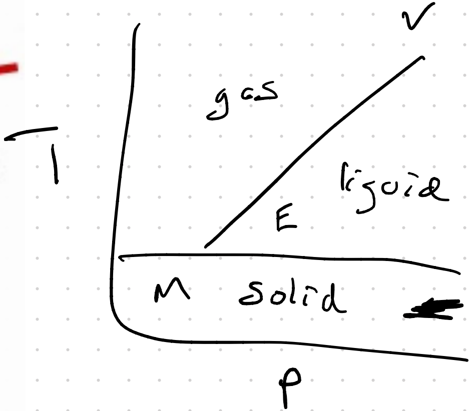
explain relative amounts?

atmospheres

ice/rock cores

"adiabat" = temp/pressure gradient





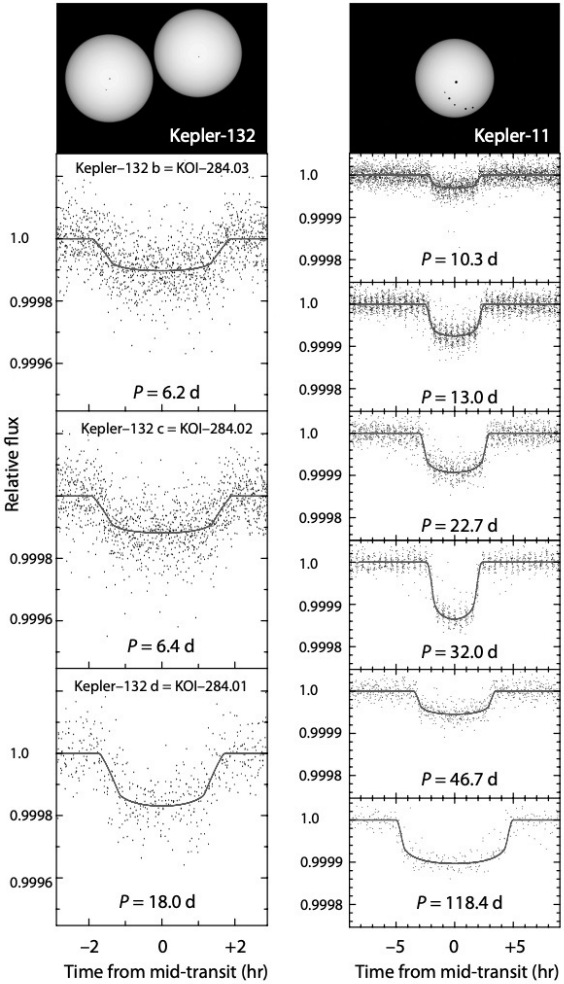
sources of internal heat? excess heat drives convection/cloud patterns

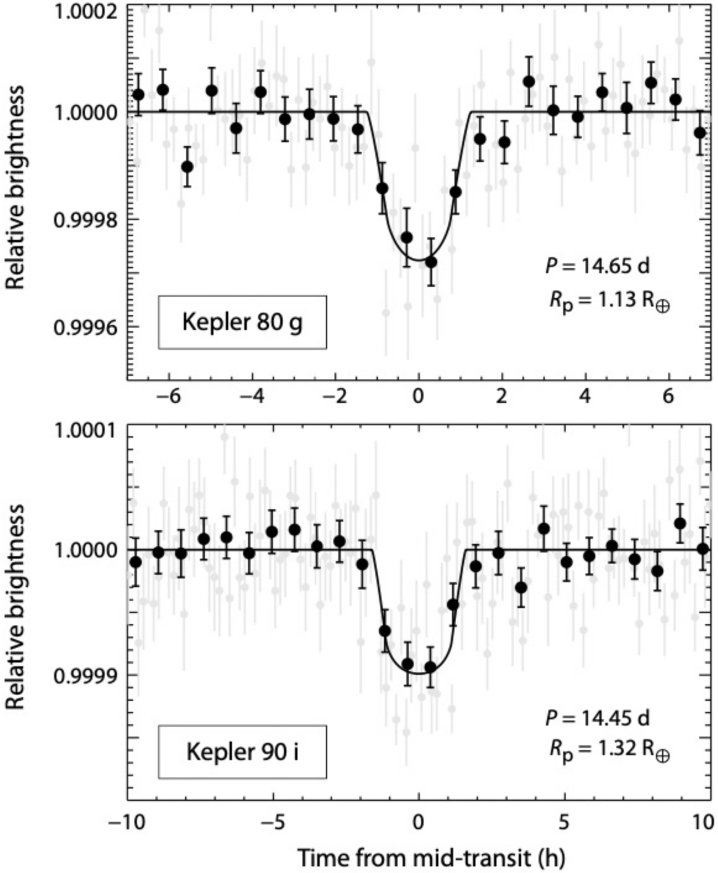
heavy element radioactivity

gravitational contraction / material differentiation

greenhouse gases (methane; Neptune)

cooling time


Kepler-132
Kepler-11
Kepler−132 b = KOI−284.03
Kepler−132 c = KOI−284.02
Kepler−132 d = KOI−284.01
Relative flux
1.0
0.9998
0.9996
0.9999
P = 6.2 d
P = 6.4 d
P = 18.0 d
P = 10.3 d
P = 13.0 d
P = 22.7 d
P = 32.0 d
P = 46.7 d
P = 118.4 d
−2
0
+2
−5
+5
Time from mid-transit (hr)


Relative brightness
1.0002
1.0000
0.9998
0.9996
P = 14.65 d
R_p = 1.13 R⊕
Kepler 80 g
−6
−4
−2
0
2
4
6
1.0001
0.9999
P = 14.45 d
R_p = 1.32 R⊕
Kepler 90 i
−10
−5
5
10
Time from mid-transit (h)

Equilibrium Temperature

$$T_{eq} = T_* \sqrt{\frac{R}{2a}} (1 - A_B)^{1/4}$$

a = semimajor axis

R = star radius

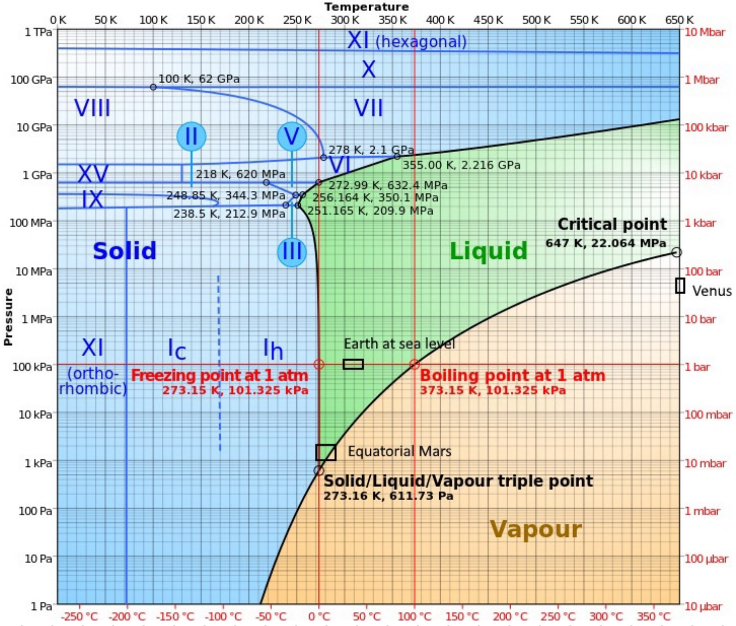
T_* = star temp

A_B = "albedo"
=> % light reflected

ability to retain heat affected by presence of atmosphere, greenhouse gases, internal heating

Habitable Zone

range of orbits around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure



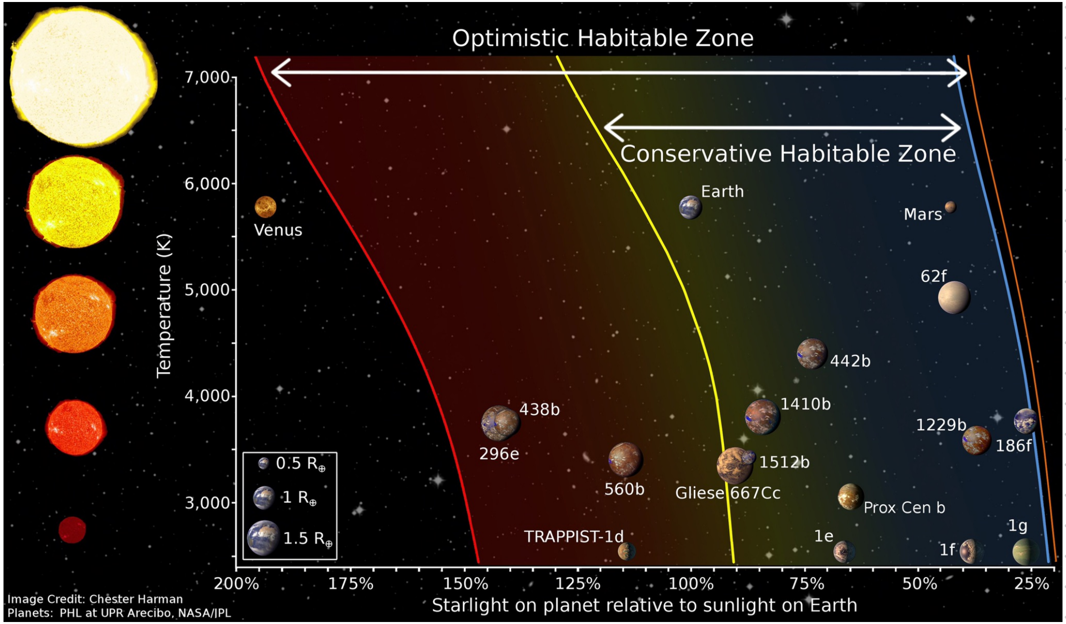
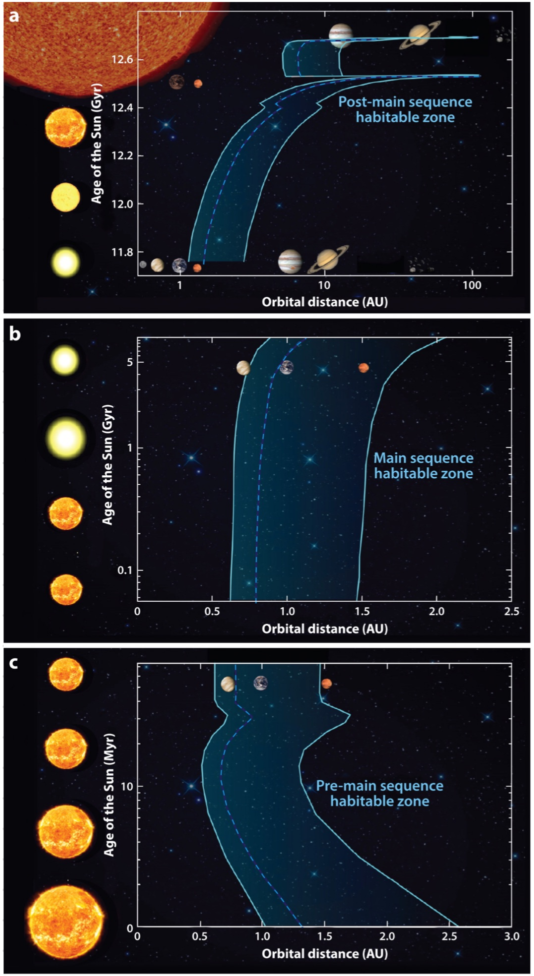


Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/IPL



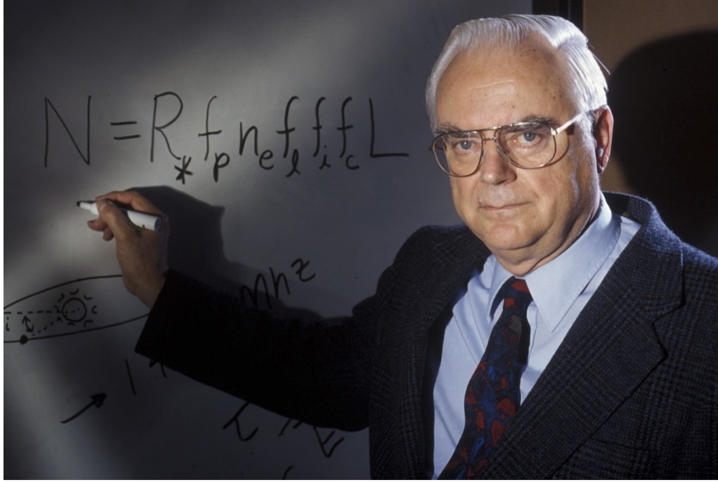
Kaltenegger L. 2017.
Annu. Rev. Astron. Astrophys. 55:433–85

what about moons ?

The Drake Equation

30 Nov 1961

60 years ago!



Frank Drake

The number of detectable civilizations in the Milky Way galaxy

The fraction of stars that host planets

The fraction of those planets on which life evolves

The fraction of intelligent life that develops communicative technologies

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

The rate at which stars are born

The number of habitable planets per planetary system

The fraction of life that evolves intelligence

The average length of time civilizations are detectable

	N	R_*	f_p	n_e	f_l	f_i	f_c	L
1.	10^{-19}	1	0.1	10^{-2}	10^{-6}	10^{-4}	10^{-10}	10^{4}
2.	10^{-8}	1	0.1	0.1	0.001	0.001	0.0001	5,000
3.	10^{-9}	1	0.1	1.5	0.01	10^{-6}	0.0001	5,000
4.	10^{-4}	1	0.1	4	0.01	10^{-7}		50,000
5.	10^{-6}	1	0.1	3	1/3	0.19	5×10^{-7}	200
6.	10^{-9}	1	0.1	2	1/5000	$1/10^{6}$	1/50	2000
Ray	0.002	1	0.2	2	1	10^{-5}	1	500
Bill	200	1	0.1	2	1	1	1	1000