Introduction to Astronomy and Astrophysics I
Lecture 5

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Some concerns

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What kind of questions will be asked in the exam?
Your notes are sparse. Where can we read more elaborately about the topics covered in class?

If you don't know coding, now is the time to learn

I strongly recommend learning Python. It is the most commonly used language in a lot of different areas.
See: https://web.iucaa.in/∼ace/programs/

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- inverted - brighter objects have lower magnitude
- measurements relative
- For small changes, a x fractional change in flux produces a x change in magnitude

Vega magnitude

The most widely used magnitude system through the year 2000 was based on a set of normalizing constants derived from the spectrum of the bright star Vega. We have now moved to *absolute* systems based on calibrations in terms of physical flux units.

The STMAG system - flux per unit wavelength

$$m_\lambda(\lambda) = -2.5 \log_{10} F_\lambda(\lambda) - 21.1$$

where $F_\lambda(\lambda)$ is the spectral flux density per unit wavelength of a source at the top of the Earth's atmosphere in units of erg s^{-1} cm^{-2} $Å^{-1}$. This is also known as the *STMAG* system because it is standard for the Hubble Space Telescope. For more details, see the Synphot User's Guide at STScI.

AB magnitudes - flux per unit frequency

The corresponding system based on flux per unit frequency is

$$m_\nu(\lambda) = -2.5 \log_{10} F_\nu(\lambda) - 48.6$$

where $F_\nu(\lambda)$ is in units of erg s^{-1} cm^{-2} Hz^{-1} .
This is also known as the *AB* system. This system has been adopted by the Sloan Digital Sky Survey,GALEX, JWST.

Jansky- used in FIR and radio astronomy

1 Jy = 10^{-23} erg/sec/Hz/cm^2

The conversion between AB magnitude m and flux density f of a star in Janskies is: f = 3631 Jy $\times 10^{-0.4m}$

Caveats

- narrow band fluxes measured using broad bands (*UBVRIJHK* - calibration problems
- calibration done not with laboratory standards, but with *standard stars*
- Many filter systems - Johnson *UBVRI*, Gunn *ugriz*

Surface brightness

is the magnitude or flux per unit solid angle - mag/arcsec^2 (optical), Jy/beam (radio), MJy/str (IR)

Absolute magnitude - luminosity measure

$$M = m - 5((\log_{10} D_L) - 1)$$

for cosmological distances, D_L is the luminosity distance.

Distance Modulus

The distance modulus equation can be written as:

$$\mu = m - M = 5 \log_{10}(D_L) - 5 \quad (1)$$

- μ is the distance modulus.
- D_L is the distance in parsecs.

Interpreting the Distance Modulus

- If $\mu > 0$, the star is farther than 10 parsecs.
- If $\mu < 0$, the star is closer than 10 parsecs.
- Distance modulus can be rearranged to solve for distance:

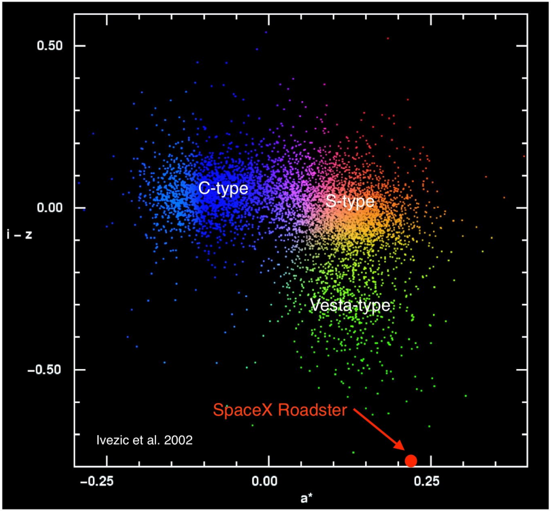
$$D_L = 10^{(\mu+5)/5} \tag{2}$$

Color in astronomy

$B - V = m_B - m_V$
$R - K = m_R - m_K$
Shorter wavelength filter is always placed first, by convention. What does a low value of color indicate? Can color be negative? Why is color important?

How to find this car in space?

How to find Musk's roadster?

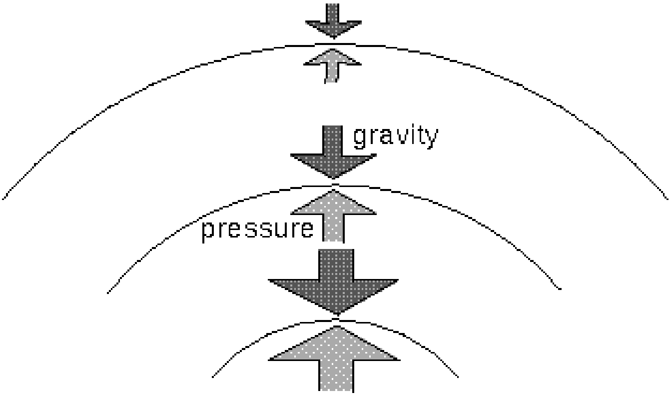


What is a star?

1. it is bound by self-gravity
2. it is powered by an internal energy source

If any of these conditions is violated, the star ceases to be a star.

Why are stars in equilibrium?



Deeper layers have more gravity compression, so they have greater outward pressure to compensate.

Hydrostatic equilibrium

$$\rho \frac{d^2 r}{dt^2} = -G \frac{M_r \rho}{r^2} - \frac{dP}{dr}$$

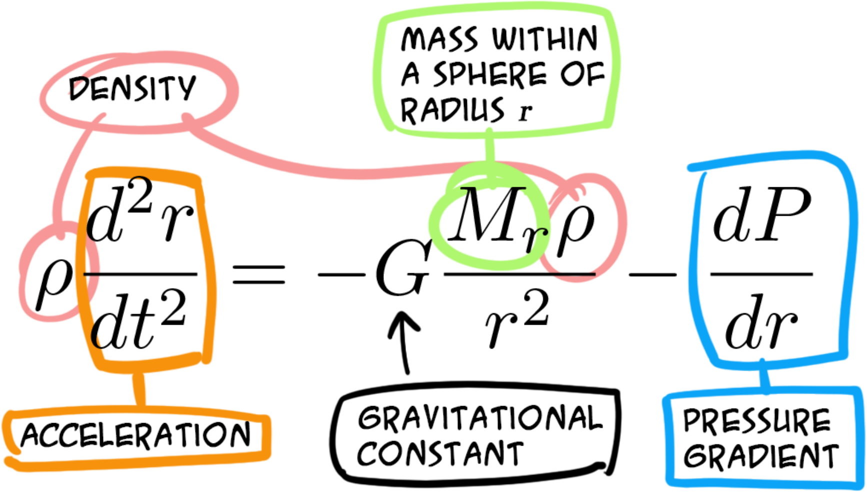
DENSITY

MASS WITHIN A SPHERE OF RADIUS r

ACCELERATION

GRAVITATIONAL CONSTANT

PRESSURE GRADIENT



$$\rho \frac{d^2 r}{dt^2} = -G \frac{M_r \rho}{r^2} - \frac{dP}{dr}$$

assumptions - no magnetic field, star is not rotating, GR not important!

Eddington Luminosity

- Named after Sir Arthur Eddington (1882-1944)
- Represents the maximum luminosity a star can achieve while maintaining hydrostatic equilibrium
- Balance between radiation pressure outward and gravitational force inward
- Crucial concept in understanding stellar evolution and black hole accretion

Key Physical Principles

- Radiation pressure: Outward force from photons
- Gravitational force: Inward pull of gravity
- Electron scattering: Primary interaction between photons and matter
- Hydrostatic equilibrium: Balance of forces in a star

Deriving the Classical Eddington Luminosity

1. Start with force balance:

$$F_{\text{rad}} = F_{\text{grav}}$$

2. Radiation force (assuming Thomson scattering):

$$F_{\text{rad}} = \frac{L\sigma_T}{4\pi r^2 c}$$

3. Gravitational force:

$$F_{\text{grav}} = \frac{GMm_p}{r^2}$$

Deriving the Classical Eddington Luminosity (cont.)

4. Equate forces and solve for L:

$$\frac{L\sigma_T}{4\pi r^2 c} = \frac{GMm_p}{r^2}$$

$$L_{\text{Edd}} = \frac{4\pi GMm_p c}{\sigma_T}$$

5. Where:
   - L_{Edd}: Eddington luminosity
   - G: Gravitational constant
   - M: Mass of the object
   - m_p: Proton mass
   - c: Speed of light
   - σ_T: Thomson scattering cross-section

Beyond Thomson Scattering

- Classical Eddington limit assumes only Thomson scattering
- In reality, other radiation processes contribute:
  - Bound-free absorption (photoionization)
  - Free-free absorption (bremsstrahlung)
- These processes can significantly modify the Eddington limit
- Particularly important in high-temperature, high-density environments

Modified Eddington Luminosity

- Total opacity: $\kappa = \kappa_T + \kappa_{bf} + \kappa_{ff}$
- Modified Eddington luminosity:

$$L_{\text{Edd,mod}} = \frac{4\pi GMc}{\kappa}$$

- Where:
  - κ_T: Thomson scattering opacity
  - κ_{bf}: Bound-free opacity
  - κ_{ff}: Free-free opacity
- Generally, $L_{\text{Edd,mod}} < L_{\text{Edd,classical}}$

Importance in Stellar Physics

- Sets an upper limit on stellar masses
- Explains instabilities in very massive stars
- Influences late stages of stellar evolution
- Crucial in understanding supernovae mechanisms

Applications in (Supermassive) Black Hole Physics

- Limits accretion rates onto black holes
- Explains self-regulation in active galactic nuclei (AGN)
- Used to estimate black hole masses from observed luminosities
- Important in understanding quasar feedback and galaxy evolution

Further Reading

Further reading: "Accretion Power in Astrophysics" by Frank, King, & Raine

Most stellar equations can be derived from simple conservation laws

- Conservation of mass
- Conservation of momentum
- Conservation of energy

Energy Transport in stars

- Conduction
- Radiation
- Convection - “convection in stars proceeds under rather malicious conditions: turbulent motion transports enormous fluxes of energy in a very compressible gas, which is stratified in density, pressure, temperature, and gravity over many powers of ten.” – KWW

What is an equation of state?

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Ideal gas equation of state: $P = nkT/V$
Non-relativitic degenerate electron gas: $P = K(n/V)^{5/3}$
Relativistic degenerate electron gas: $P = K'(n/V)^{4/3}$
Why do we speak of electrons as “electron gas”?

Polytropic equations of state

If ρ is independent of temperature, then $\rho = \rho(P)$ and we can write

$$P = K\rho^{\gamma} = K\rho^{1+1/n}$$

The value of the polytropic index n depends on whether the degenerate gas is relativistic or non-relativistic. K can be a constant or can vary from star to star, depending on the equation of state. Polytropic approach makes many simplifying assumptions and is now out of fashion.

Textbook - Stellar Structure and Evolution

by Kippenhahn, Weigert and Weiss (Springer: 2012)
Comprehensive coverage on all aspects of stellar structure and Evolution.

Fusion: Hydrogen to Helium- via proton chain

$$4\,{}^1H \rightarrow 2\,{}^2H + 2e^+ + 2\nu_e \quad (3)$$
$$2\,{}^1H + 2\,{}^2H \rightarrow 2\,{}^3He + 2\gamma \quad (4)$$
$$2\,{}^3He \rightarrow {}^4He + 2\,{}^1H \quad (5)$$

Net reaction is:
$4\,{}^1H \rightarrow {}^4He + 2\nu_e$ + energy (26.7 MeV)
Sun produces 4×10^{26} joules per second. How many of the above fusion reactions are happening per second, if the Sun's energy comes entirely from the above process?

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9.36e+37
Read about the solar neutrino problem and how it was solved.

How long will the Sun last?

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2e30*0.8/(4e9 * (86400*365 *1e9)) * 0.007

89 GYr

Chemical composition of the Sun

X mass fraction of hydrogen 0.70
Y mass fraction of helium 0.28
Z mass fraction of metals 0.02
By definition, $X + Y + Z = 1$. Z is called metallicity.

Temperature and luminosity relation for stars

For black bodies,
$\sigma T_{eff}^4 = L/4\pi R^2$
where σ is the Stefan-Boltzmann constant.
So, $L = 4\pi R^2 \sigma T_{eff}^4$
Stellar spectra are well approximated by a black body with $T_{eff} \sim T_{photosphere}$, since bulk of the light that reaches us comes from the photosphere.
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Thus, it natural to expect some correlation between luminosity and temperature. When the sun becomes a red giant it's radius will be about 2 AU. It's surface temperature will be about 3000 K. What will be it's luminosity relative to its present luminosity?

Translating observations to physical parameters using physical laws