ASTR 1040: Stars & Galaxies

Whirlpool Galaxy M51

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Lecture 11 Tues 20 Feb 2018
zeus.colorado.edu/astr1040-toomre

Logistics

- Read Chap 15.1: Properties of Stars with care, then 15.2: Patterns among Stars
- Mid-Term Exam 1 returned, with answers, plus cribsheets
- Homework #4 also returned graded
- Observatory #3 this Wed 21 Feb, by signup – we try again! (Mixed forecast)

Topics for Today

- How to classify other stars?
- Vital work by Annie Jump Cannon in devising a sensible "spectral sequence" for stars
- Why temperature and spectral lines are closely linked in classifying stars O B A…M
- Cecilia Payne-Gaposhkin and the "Saha" equation to predict spectral line strengths
- Roadmap to the stars: Hertzsprung-Russell (H-R) diagram

So did we really love this exam?

RESULTS FROM FIRST MID-TERM EXAM

FIRST MID-TERM EXAM

- Grade boundaries, based on 110 points (graded on a "curve"):

- If 99/110 (90%) or over, A's [44%]
- 87/110 (79%) or over, B's [46%]
- 82/110 (75%) or over, C's [6%]

Also +, plain, and – within these ranges

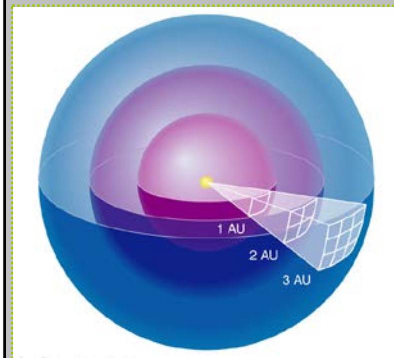
Go through answer sheet – and talk to us if do not understand our choices. Keep exam + answers for future review (comp final)

Most Basic Problem in Astronomy

Star of given APPARENT BRIGHTNESS could be either
A. very luminous star far away
B. low luminosity star closer by

Need to know the DISTANCE to the star

Inverse Square Law of Brightness



Apparent Brightness ≈ L_o / (distance)^2

Stellar Luminosity

- What we *measure*: APPARENT BRIGHTNESS

  or how bright it appears to us here on Earth

- What we *want to know*: (absolute) LUMINOSITY

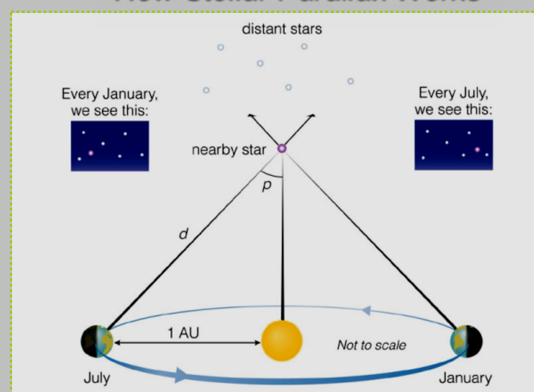
  or how much energy is emitted (*joules/sec or watts*)

- Need to know *DISTANCE* to the star

Parallax – to determine distance

- Measure the *apparent movement of stars* over a year
- Movement is caused by Earth's movement around the Sun
- Closer objects will move more than farther objects

How Stellar Parallax Works



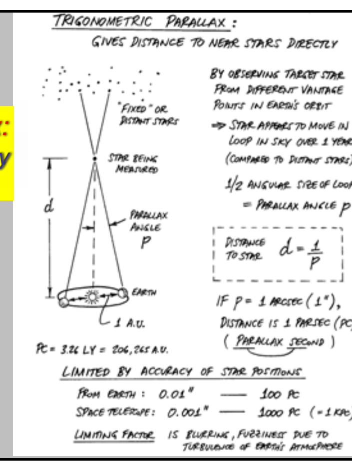
Class self-demo of parallax

- Your nose is the Sun
- Your left eye is the Earth in January
- Your right eye is the Earth in June

Watch the apparent motion of your thumb against a distant reference point (repeat at arm's length)

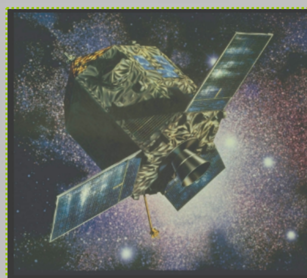
Which *"move" more* -- closer or farther objects?

Stellar Parallax: measuring nearby distances



Best parallax measurers:
Hipparcos satellite 1989-1993
GAIA satellite Dec 2013 →

- Space measurements not affected by atmosphere
- Measurement made many times until accurate to ~0.001 arcsec (Hipparcos →1,600 light years)
- 100,000 stars mapped; 2.5 million lesser accuracy
- GAIA: 10 micro-arcsec, billion stars; 10,000+ ly



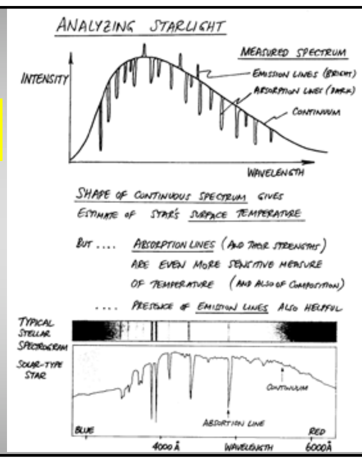
Clicker recall: What is net inward force on evacuated "oil barrel"?

- A: 200 lbs
- B: 500 lbs
- C: 2,000 lbs
- D: 5,000 lbs
- E: 50,000 lbs

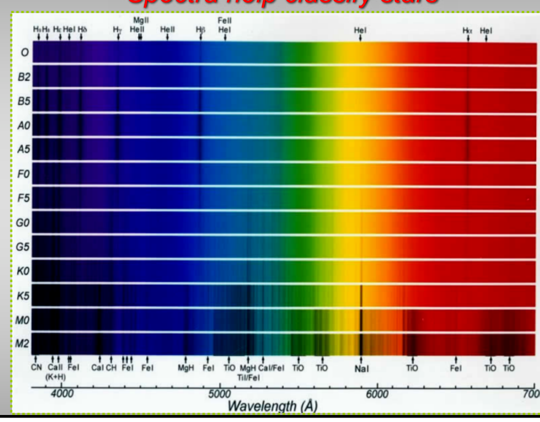
REMINDER

Measuring Surface TEMPERATURE

Shape of spectrum good … but spectral lines much better



Spectra help classify stars



A bit of history: Classifying Stars

World War I, Harvard College observatory

Women were hired by Pickering as "calculators" to help with a new survey of the Milky Way

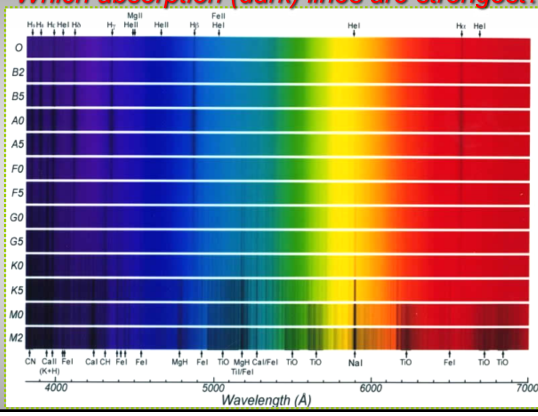
Most had studied astronomy, but were not allowed to work as scientists

Devising the strange temperature code

- Original classification of spectra (1890) was:
  A = strongest hydrogen feature
  B = less strong hydrogen …C, D, etc.
- Annie Jump Cannon realized that a different sequence made more sense (~1910)

→ O B A F G K M !!

Which absorption (dark) lines are strongest?



Spectral Classification: O B A F G K M

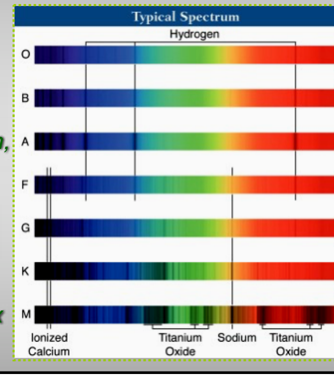
Which ABSORPTION lines are strongest

Hottest stars: O B ionized helium only

Hot stars: A F helium, hydrogen

Cooler stars: G hydrogen, heavier atoms

Coolest stars: M molecules, (complex absorption bands)



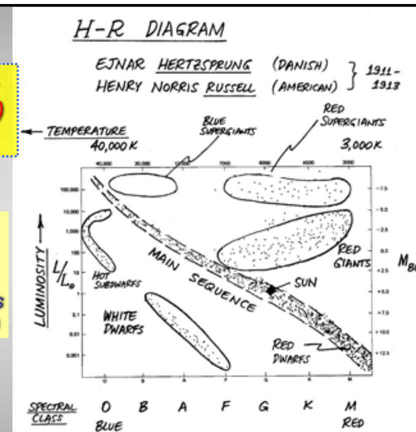
H - R Namesakes

Ejnar Hertzsprung

Henry Norris Russell

Hertzsprung-Russell (H-R) Diagram

Luminosity (magnitude) vs Spectral class (temperature)

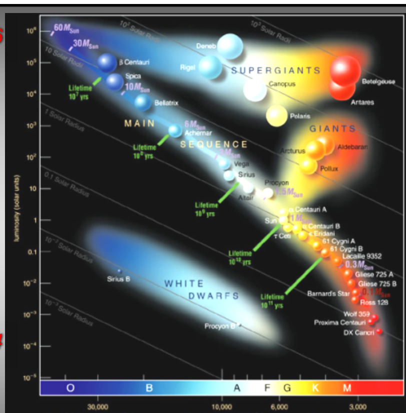


Luminosity

(solar units)

10^6

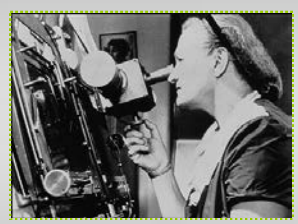
10^{-4}



40,000 ← Temperature 3,000

Cecelia figured out WHY stellar spectra are so different: TEMPERATURE

- She showed that SURFACE TEMPERATURE is the big factor (not composition)
- She used the newly-devised SAHA EQUATION, estimating how many electrons remain attached to atoms as temperature is changed (or the level of ionization)



Cecelia Payne-Gaposchkin
(Harvard PhD thesis 1925)

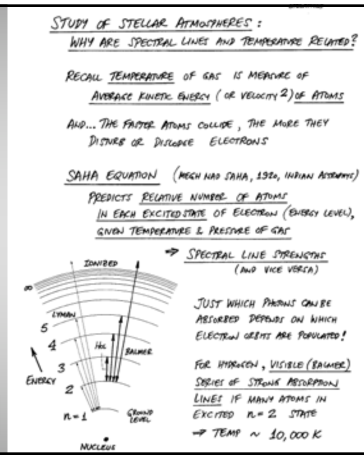
O B A F G K M → decreasing temperature

Why temperature and spectral lines are linked?

SAHA gives the answer:

can estimate "population of different energy levels" in H, He …

and ionization (continuous crash, bang, relax, do it again)


STUDY OF STELLAR ATMOSPHERES:
WHY ARE SPECTRAL LINES AND TEMPERATURE RELATED?

RECALL TEMPERATURE OF GAS IS MEASURE OF AVERAGE KINETIC ENERGY (OR VELOCITY 2) OF ATOMS

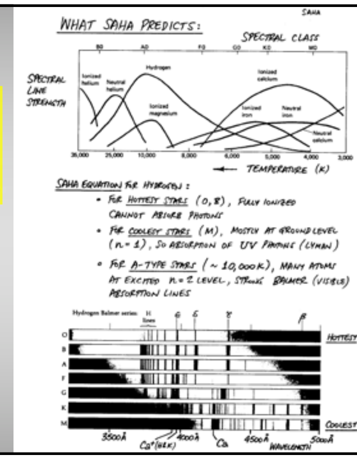
AND… THE FASTER ATOMS COLLIDE, THE MORE THEY DISTURB OR DISLODGE ELECTRONS

SAHA EQUATION (MEGH NAD SAHA, 1920, INDIAN ASTRONOMER)
PREDICTS RELATIVE NUMBER OF ATOMS IN EACH EXCITED STATE OF ELECTRON (ENERGY LEVEL), GIVEN TEMPERATURE & PRESSURE OF GAS
→ SPECTRAL LINE STRENGTHS (AND VICE VERSA)

JUST WHICH PHOTONS CAN BE ABSORBED DEPENDS ON WHICH ELECTRON ORBITS ARE POPULATED!

FOR HYDROGEN, VISIBLE (BALMER) SERIES OF STRONG ABSORPTION LINES IF MANY ATOMS IN EXCITED n = 2 STATE
→ TEMP ~ 10,000 K

SAHA predicts spectral line strengths with temperature

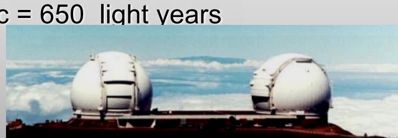

WHAT SAHA PREDICTS:

SAHA EQUATION FOR HYDROGEN:
- FOR HOTTEST STARS (O, B), FULLY IONIZED CANNOT ABSORB PHOTONS
- FOR COOLEST STARS (M), MOSTLY AT GROUND LEVEL (n = 1), SO ABSORPTION OF UV PHOTONS (LYMAN)
- FOR A-TYPE STARS (~ 10,000 K), MANY ATOMS AT EXCITED n = 2 LEVEL, STRONG BALMER (VISIBLE) ABSORPTION LINES

Puzzle Clicker: Stellar Parallax

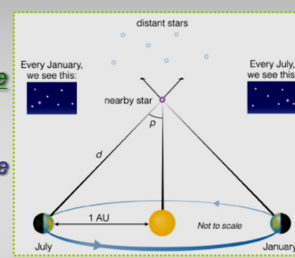
- The biggest ground-based telescopes with adaptive optics can measure stars positions with accuracies of about 0.05 arcsec. How far away could they map the positions of stars via parallax?
- A. 2 pc = 6.5 light years
- B. 20 pc = 65 light years
- C. 200 pc = 650 light years

B.



Parallax

- B. maximum distance is set by the accuracy with which you can measure positions in the sky (space does better than ground)



Distance (pc) =
1 / 0.05 arcsec
= 20 pc = 65 ly

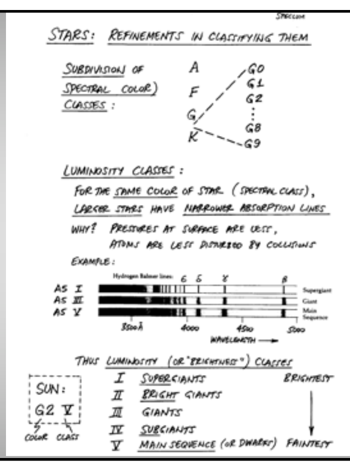
d (in parsecs) = 1 / p (in arcsec)

Further refinements:

DECIMAL SUBDIVISION

LUMINOSITY CLASSES
how narrow are absorption lines

Sun is:
G2 V
COLOR CLASS


STARS: REFINEMENTS IN CLASSIFYING THEM

SUBDIVISION OF SPECTRAL COLOR) CLASSES:

LUMINOSITY CLASSES:
FOR THE SAME COLOR OF STAR (SPECTRAL CLASS), LARGER STARS HAVE NARROWER ABSORPTION LINES
WHY? PRESSURES AT SURFACE ARE LESS, ATOMS ARE LESS DISTURBED BY COLLISIONS
EXAMPLE:

THUS LUMINOSITY (OR "BRIGHTNESS") CLASSES
I SUPERGIANTS — BRIGHTEST
II BRIGHT GIANTS
III GIANTS
IV SUBGIANTS
V MAIN SEQUENCE (OR DWARFS) — FAINTEST

SUN: G2 V (COLOR, CLASS)

Magnitudes: Apparent vs Absolute

- Giving measures to stellar luminosities
- Built on choices made by Greeks!

Stellar MAGNITUDES

Weird system: brighter is smaller magnitude, even negative!

Of cultural importance, even if a bit confusing (secret society!)

MAGNITUDES : BLAME WEIRD SCALE ON GREEKS .... AND REPAIR BY HERSCHEL

1. GREEKS ASSIGNED
   BRIGHTEST STAR — MAGNITUDE 1
   ⋮
   FAINTEST STAR VISIBLE TO EYE — MAG 6 } DIFFERENCE OF 5 "MAGNITUDES"
2. HERSCHEL CONCLUDED THIS WAS ABOUT 100 : 1 IN BRIGHTNESS
   ASSIGNED APPARENT MAGNITUDE $m_V = 0$ TO BRIGHT STARS VEGA AND RIGEL KENT
3. NOW THE PRESENT SYSTEM :
   BRIGHTNESS UP ↑ BY FACTOR 2.512
   MAGNITUDE DOWN ↓ BY 1 UNIT

MAGNITUDE	RELATIVE BRIGHTNESS
5	1.0
4	2.512
3	6.310 = $(2.512)^2$
2	15.849 = $(\cdot)^3$
1	39.811 = $(\cdot)^4$
0	100.000 = $(\cdot)^5$

Measuring BRIGHTNESS

magnitudes

m

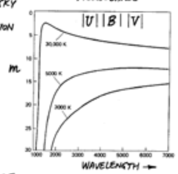
apparent mag: what looks like in sky

M

absolute mag: what would look like if at 10pc distance (LUMINOSITY)

MEASURES OF BRIGHTNESS — FIRST STARS, NOW GALAXIES...

1. APPARENT MAGNITUDE m
   ACTUALLY MEASURE HOW BRIGHT AN OBJECT APPEARS IN SKY
   DEPENDS ON SPECTRAL REGION (COLOR) WHERE MEASURED
   USE FILTERS :
   U — ULTRA-VIOLET ⇒ m_U
   B — BLUE — m_B
   V — VISUAL — m_V
   ETC...



2. BOLOMETRIC MAGNITUDE
   ADD UP BRIGHTNESS AT ALL WAVELENGTHS ... BUT DIFFICULT TO MEASURE
3. ABSOLUTE MAGNITUDE M
   MAGNITUDE STAR WOULD HAVE IF AT DISTANCE OF 10 PARSECS (32.6 LY)
   NEED m AND DISTANCE !

(Slightly) screwy world of MAGNITUDES

IF can estimate distance, then can determine M given m

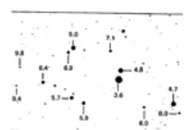
M = m if at distance 10pc

MAGNITUDES: HANDY RESULTS TO RECALL

5 MAGNITUDES = FACTOR OF 100 IN BRIGHTNESS

MAGS. CAN BE NEGATIVE

BOL. MAG. < APPARENT MAG.



APPARENT MAGNITUDES OF STARS (NEGATIVE IMAGES)

ABSOLUTE MAGNITUDE M < APPARENT MAG m IF DISTANCE > 10 PC (32.6 LY)

M > m IF DISTANCE < 10 PC

VISUAL MAGNITUDES OF "NEARBY OBJECTS"

Object	Apparent Magnitude (m_v)	Distance (ly)	Absolute Magnitude (M_v)
Sun	−26.7	1.5×10^{-5}	+ 4.8
Moon (full)	−12.5	4.0×10^{-8}	+32.1
Venus (at brightest)	− 4.4	4.4×10^{-6}	+29.9
Sirius	− 1.5	8.6	+ 1.4
Rigel Kent (Alpha Centauri)	0.0	4.3	+ 4.4
Vega	0.0	25.0	+ 0.5
Deneb (Alpha Cygni)	+ 1.3	1.6×10^{3}	− 7.2
G51-15 (nearby star)	+14.8	11.9	+17.0
Andromeda Galaxy	+ 3.5	2.25×10^{6}	−21.2

Clicker: Stellar puzzle B.

- Two stars, Antony and Cleopatra, are both of spectral class M3, and of the same apparent brightness (magnitude) in the sky. Cleopatra shows narrow absorption lines in her spectrum, Anthony broad ones. Which star must be far more distant?
- A. Antony
- B. Cleopatra

Estimating the size of a star – its RADIUS

Stefan-Boltzmann

MEASUREMENTS OF STARS :

TEMPERATURE (FROM SPECTRAL LINES)

BRIGHTNESS
DISTANCE ("NEARBY" STARS < 100 pc) } ⇒ LUMINOSITY

RECALL STEFAN – BOLTZMANN LAW :

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

L: LUMINOSITY (MEASURED); R: STAR'S RADIUS (UNKNOWN); σ: CONSTANT; T: TEMPERATURE (MEASURED)

⇒ LUMINOSITY & TEMP ⇒ RADIUS

BUT HOW TO GET THE MASS ?

(TRICKIER : USE BINARIES)