Astro 210
Lecture 30
April 6, 2018

Announcements:

- **HW8 due online in PDF, today 5:00 pm**
- HW9 posted, due next Friday
- **Solar Observing raindates next week** April 9–14
  Mon, Tue, Wed, Thurs. 11:15 am to 2:45 pm
  Campus Observatory
  allow 20-30 minutes. take **selfie** with telescope
- Night Observing: no clear last night so
  substitute exercise posted on Moodle, due today 5:00 pm

Stars: the Story Thus Far

Game plan:
1. give stars a physical–find luminosity, mass, temperature
2. compare with Sun and with each other
3. use these as input for theory for stellar evolution

Thus far:
- luminosity: light energy output ("wattage") of star
- flux depends on star L but also distance: $F = L/4\pi d^2$

Q: how to get stellar distances?

Q: brightness scales: physical units? astronomer units?
- $m_2 - m_1 = -2.5 \log_{10}(F_2/F_1)$
- $m_{\mathrm{Vega}} = 0$ by definition

`www: the brightest stars, down to` 3.0^{mag}
Q: note patterns in apparent magnitude?

Absolute Magnitude

absolute magnitude M = apparent mag at $d_0 = 10$ pc

places all stars at constant fixed distance
$\longrightarrow$ a stellar "police lineup"
$\longrightarrow$ then differences in F only due to diff in L
$\longrightarrow$ absolute mag effectively measure **luminosity**

Sun: abs mag $M_\odot = 4.76$ mag
Sirius: $M_{\text{Sirius}} = +1.43$ mag
Vega: $M_{\text{Vega}} = +0.58$ mag
Polaris: $M_{\text{Polaris}} = -3.58$ mag
Q: rank them in order of descending L?

ω Immediately see that Sun neither most nor least luminous star around

Distance Modulus

define $\mu \equiv m - M$: "**distance modulus**"

$$\mu = m - M = -\frac{5}{2} \log_{10} \frac{F}{F_0} \tag{1}$$

uses ratio of actual star flux F vs "reference" flux F_0
at abs mag when at "reference" distance $d_0 = 10$ pc:

$$\frac{F}{F_0} = \frac{L/4\pi d^2}{L/4\pi d_0^2} = \left(\frac{d_0}{d}\right)^2 \tag{2}$$

so we have

$$\mu = -\frac{5}{2} \log \left(\frac{d_0}{d}\right)^2 = 5 \log \left(\frac{d}{10 \text{ pc}}\right) \tag{3}$$

- depends only on distance d, not on luminosity!
  can use as measure of distance
- for all but the nearest stars: $d > 10$ pc, so $\mu > 0$
  so $m > M$: objects are dimmer than absolute magnitude

Star Color

Recall: color related to Temperature

colder: redder; hotter: bluer

`www: objective prism spectra`

very useful to *quantify* color!

- could try spectrum peak λ_{max} – but often, absorption lines → non-blackbody spectrum
  also: full spectrum from spectrometer “expensive”
  → have to collect more light since spread out

Q: what’s a cheaper way to get color information from an image?

Note: imaging detectors are CCDs

→ ‘democratically” count all photons they see equally
  regardless of wavelength

To get color information without a spectrometer:
$\Rightarrow$ use **filter** which accepts light
only in a *range* of wavelengths: “passband”

`www: filter wheel`

$F_B \rightarrow m_B = B$: blue band, centered around $\lambda \approx 440$ nm
$F_V \rightarrow m_V = V$: “visual”, yellowish, $\lambda \approx 550$ nm
...and many others
`www: filter` λ `ranges`

images in multiple filters $\leftrightarrow$ crude spectrum

Q: how to quantify color based on filter data?

Color Index

measure color by comparing flux at different λ bands

"**color index**" : $B - V = 2.5 \log F_V / F_B + const$ $\rightarrow$ ratio of fluxes
Fix const: $B - V = 0$ for star with $T = 10,000$ K (e.g., Vega)
index measures T!
`www: color and spectra`

ex: `www: Orion`
Betelgeuse reddish, $B - V = 1.5$; $T \sim 3300$ K
Rigel bluish, $B - V = -0.1$; $T \sim 12,000$ K

Stars: Temperatures and Spectral Types

Note: color index is useful but crude measure of star T

in today's Director's Cut Extras:
how to use full spectrum of star to get accurate temperatures

this procedure *classifies* star "**spectral types**"
which correspond to different temperatures
hottest $\rightarrow$ coolest: **OBAFGKMLT**

how to remember?
classic mnemonic: "Oh be a find girl/guy kiss me"
∞ HW9: make your own mnemonic for bonus points and prizes!

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Star Luminosity

color and/or Spectral type $\rightarrow$ temperature T

stellar luminosity depends on T
but also on radius R:
since surface flux $F = L/\text{area} = \sigma T^4$

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

so for fixed T (same spectral type), $L \propto R^2$
$\rightarrow$ bigger stars $\rightarrow$ bigger emitting surface $\rightarrow$ higher L

iClicker Poll: Star Temperature and Luminosity

Vote your conscience!

For large sample of stars, measure L and T for each
plot points on diagram of L vs T

What will the data show?

A random scatter: stars have large range of L, and of T, and in any combination

B tight clump of points: stars are nearly identical, all with very similar L and T

C a clear trend: stars have large range of L and of T but the two vary together (correlated)

D none of the above

A Stellar Census: Hertzsprung-Russell Diagram

Hertzsprung-Russell: plot L vs$T$ for lotsa stars
really, abs mag M_V vs spectra type
but these are equivalent to L and T

`www: H-R diagram`

Q: what patterns do you notice?
Q: where are most stars?
Q: where is the Sun?

Hertzsprung-Russell Diagram

for a "fair sample" of stars
(i.e., not a specially picked cluster)
trends emerge

⋆ *most* stars ($\sim 90\%$) fall on curve: **main sequence**
(including the Sun!); *"dwarfs"*
⋆ most of the rest: cooler but more luminous: **giants**
Q: how can a star be cool yet more luminous?
⋆ a rare few: hot but luminous: **supergiants**
⋆ not rare but dim and hard to find:
very hot but very low-L objects: **white dwarfs**
Q: how can a star be hot yet underluminous?

Q: what does the HR diagram tell us about the Sun?

H-R and the Sun

The Sun on H-R diagram:

- on the main sequence
- position is in the middle of the curve

but the main sequence is where most stars are found!

thus: *the Sun is a typical star!*

- lies in heart of main sequence L vs T trend
- neither most nor least luminous, not hottest or coolest

Mass

Most important parameter of a star!

Q: why is stellar mass hard to determine?

Q: when/how can mass be measured?

For single stars:
mass determination difficult, very indirect

But can find masses for **binary** systems:
two stars orbiting common center of mass
diagram: orbits

measure P, r_1, r_2
get m_1, m_2 from Newton's version of Kepler's 3rd law

$$m_1 + m_2 = \frac{4\pi^2}{G} \frac{r^3}{P^2} \tag{5}$$

and $m_1/m_2 = r_1/r_2$

problem: must measure r's *Q: how?*

Types of Binary Stars

visual binary

can see both stars!

`www: visual binary orbit`

eclipsing binary

stars pass in front of each other

can see in light curve:

diagram: light curve $\rightarrow$ get rs from timing of eclipses

spectroscopic binary

periodic Doppler shifts in spectrum

see $\Delta\lambda_1$, $\Delta\lambda_2$

$\rightarrow$ radial velocity $v_r/c = \Delta\lambda/\lambda_0$

then $v_1 = r_1\omega = 2\pi r_1/P$

can solve for r!

Director's Cut Extras

Stellar Temperatures

instead of broadband colors, take full stellar *spectrum*
$\longrightarrow$ contains much more information

roughly ("zeroth approximation"): stars are blackbody emitters
$\triangleright$ spectrum roughly Planckian, $\lambda_{\rm max} \rightarrow T$ (Wien's law)

more realistically: stars are not perfect blackbodies
Q: why? hint–what does the Sun's spectrum look like?
Q: how can we make use of the non-blackbody aspects?

Stars: Spectral Types

solar & stellar photospheres cooler than underlying material
$\rightarrow$ observed spectrum shows *absorption lines*

- "barcode" of elements in star, but also
- distorts spectrum from blackbody

Annie Jump Cannon, Harvard $\sim$ 1900:
studied many stellar spectra, and found patterns:

- different atomic lines show different *relative* strength in different stars *Q: meaning?*
- linestrength variations not random: follow pattern

$\star$ can *classify* stars according to spectrum
$\rightarrow$ spectral types: originally named ABC...

Physical Origin: What Spectral Types Mean

first consider one atom's lines:
Balmer series in hydrogen: $n = 2 \rightarrow n \geq 3$

diagram: Balmer line strength vs $\star$ atmosphere temperature T k
as T increases, strength increases $\rightarrow$ max $\rightarrow$ decreases

Q: why this pattern?

What's going on?

Balmer needs $n = 2$ H atoms:

$\rightarrow$ need neutral atoms, but in 1st excited state

temperature "fine tuning" required

too cold: most in ground state $n = 1$

hot: most ionized ($n = \infty$)

Balmer $\rightarrow$ intermediate T!

similar issues with other lines

$\rightarrow$ each has "favorite" temperature where strongest

Q: so what sets spectral types?

Q: M, L, T types include molecular lines–what does this mean?

Q: O stars have singly ionized He, doubly ionized carbon what does this mean?

Key point:

spectral type $\Leftrightarrow T$

- a better, finer scale than color index
- gold standard for temperature
- when sorted by temperature, spectral types un-alphabetical
  hotter $\rightarrow$ cooler: **OBAFGKMLT**

how to remember?

classic mnemonic: "Oh be a find girl/guy kiss me"

HW9: make your own mnemonic for bonus points and prizes!

OBAFGKMLT

Spectra types $\rightarrow$ spectral features $\rightarrow$ temperature

e.g., Sun is G-type star:
most elements neutral, some heavier elements singly ionized
$\rightarrow$ intermediate temperature: 4900-5700 K

compare: O stars have high ionization states
$\rightarrow$ very high $T > 30,000$ K!
MLT stars not only neutral atoms, but even molecules
$\rightarrow$ molecule survival $\rightarrow$ very low $T < 3800$ K