Astro 210
Lecture 30
April 8, 2011

Announcements

- HW 8 due
- HW 9 available, due in 1 week
- **Solar Observing**: try again next week
  open 10:30am to 3:30 pm; allow about 30min
  info, report form online

Last time: star brightness and color

- luminosity ↔ absolute magnitude
  light energy output (“wattage”) of star

- flux ↔ apparent magnitude
  depends on star luminosity, but also distance: $F = L/4\pi d^2$

- color: measure by *ratio* of flux at different λ
  ↔ *differences* of magnitudes in different passbands
  Q: how does color depend on star distance?
  Q: what does color tell about star?

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
hotter → 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!

Star Luminosity

color and/or Spectral type → temperature T

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

$$L = 4\pi R^2 \sigma T^4 \tag{1}$$

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

Other questions arise:
- *why* do most stars lie on the main sequence?
- what controls their position on the diagram?
- what's up with the giants, supergiants, and white dwarfs?

to understand these, need *theory* of stars

The Facts of Life for Stars

Fact: stars constantly radiates energy

and at a huge rate!

for the Sun: $dE/dt = L_\odot = 4 \times 10^{26}$ Watts!

Fact: stars have a finite ($\neq \infty$) mass

and thus a finite fuel supply (whatever that fuel may be)

Fact: Energy is conserved

no free lunch!

Q: therefore?

How Does the Sun Shine?

The Sun radiates: shines from thermal radiation

- recall: surface flux $F_{\mathrm{surf},\odot} = \sigma T^4_{\mathrm{surf},\odot} = 60\ \mathrm{MWatt/m^2}$

- total power output = rate of energy emission = luminosity

$$L_\odot = 4\pi R^2_{1\ \mathrm{AU}} F_\odot(1\ \mathrm{AU}) = 3.85 \times 10^{26}\ \mathrm{Watts} \tag{2}$$

→ the Sun is a 4×10^{26}-Watt lightbulb

- But also: the Sun has *constant* temperature, luminosity (over human timescales $\gtrsim$ centuries)

Q: how is the Sun unlike a cup of coffee?

The Sun is Not a Cup of Coffee

Coffee Thermodynamics

Demo: cup of coffee: cools
themodynamic lesson:

- left alone, hot coffee cools (surprise!)
  → energy radiated, not replaced
- to keep your double-shot soy latte from cooling
  need Mr. Coffee machine–energy (heat) source

Contrast with the Sun

- Sun doesn't cool
  but energy *is* radiated, at enormous rate
- ergo: something must replace the lost energy

▷ What is solar heat source?
→ a mystery in Astronomy until the 20th century

Q: possible energy/heat sources which Sun taps?
Q: how to test/compare which are important?

Energy Conservation and the Sun

recall: power is energy flow rate $L = dE/dt$
if lose energy at constant rate,

$$\boxed{E_{\text{lost}} = L\tau}$$

with $\tau =$ "lifetime" of Sun

Energy conservation:
energy supply = lifelong energy loss

The game:

- compute/estimate supply ("battery") for each candidate solar energy "reservoir"
- assume Sun has some way to "tap" each source
  → convert energy to heat (thermal atom motion)
  → keep T_{surf} hot, replenish radiated energy
- then see how long each source could light up the Sun
- important source(s) ≡ long-lived:
  $\tau_{\text{source}} = E_{\text{res}}/L_{\odot} > \tau_{\odot} = 5$ billion yr

Possible Solar Energy Sources

- Gravity

if Sun contracts → release grav. P.E.

estimate gravitational energy "reservoir"
approximate Sun as uniform sphere:
$PE_{\rm grav} = -3/5\ GM_{\odot}^2/R_{\odot} = 2 \times 10^{41}$ Joules
$\rightarrow E_{\rm contract} = -PE$

if grav energy fuels the Sun, lasts for
$\tau_{\rm grav} = E_{\rm contract}/L = 5 \times 10^{14}$ sec $= 17$ Myr
but: Sun, SS age is 4.6 billion yrs
→ not enough!

- Chemical Energy

if entire Sun interior made of TNT (!)
burning → release chemical energy → heat
but: $\tau_{\text{chem}} = 20{,}000$ years! yikes!

- Rotational Energy

Sun spins, has rotational energy
(rotational equivalent of kinetic energy)

$$E_{\text{rot}} = \frac{1}{2} I \omega^2 \approx \frac{1}{5} M_\odot (\omega_\odot R_\odot)^2 \tag{3}$$

if made Sun spin down (somehow)
convert spin energy to heat
but: $\tau_{\text{rot}} \approx 400$ years!!

Lesson: Sun requires **enormous** energy source

The **only** viable candidate:

- Nuclear Energy

The Sun is a vast nuclear reactor
in hot core, hydrogen converted to helium
by nuclear reactions

Note: needed *quantitative* estimates of burn times
to answer *qualitative* question "What powers the Sun?"
→ the power of (and necessity of) number crunching!

Director's Cut Extras

Stellar Temperatures

instead of broadband colors, take full stellar *spectrum*
→ contains much more information

roughly ("zeroth approximation"): stars are blackbody emitters
▷ spectrum roughly Planckian, $\lambda_{\text{max}} \to T$ (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
→ observed spectrum shows *absorption lines*

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

Annie Jump Cannon, Harvard ∼ 1900:
studied many stellar spectra, and found patterns:

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

★ can *classify* stars according to spectrum
→ 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

as T increases, strength increases → max → decreases

Q: why this pattern?

What's going on?
Balmer needs $n = 2$ H atoms:
→ 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 → intermediate T!

similar issues with other lines
→ 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 → cooler: **OBAFGKMLT**

how to remember?

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

HW10: make your own mnemonic for bonus points and prizes!

OBAFGKMLT

Spectra types → spectral features → temperature

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

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