Astro 210

Lecture 29

November 3, 2010

Announcements

- HW 8 available, due in class Friday
- **Solar Observing** today and tomorrow
  - ▷ schedule, report form online

Last time: The Sun–overview

Q: why doesn't the gas float away or collapse on itself?

Q: why does the Sun appear to have a sharp edge?

iClicker Poll: Solar Observing

Monday was a bust for solar observing
but yesterday was ideal; staff included your TA Rukmani

Vote your conscience!

So–did you go to solar observing yet?

A I did! And now I have that warm feeling of astro-goodness

B No...but I will go if it clears up today, I promise

C No...I will wait and count on good weather tomorrow even though the forecast is "mostly cloudy"

The Facts of Life for the Sun

Fact: the Sun constantly radiates energy
and at a huge rate: $dE/dt = L_\odot = 4 \times 10^{26}$ Watts!

Fact: the Sun has a finite ($\neq \infty$) mass
and thus a finite fuel supply (whatever that fuel may be)

Fact: Energy is conserved
no free lunch!

ω *Q: therefore?*

How Does the Sun Shine?

The Sun radiates: shines from thermal radiation

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

- total power output = rate of energy emission = luminosity

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

  $\rightarrow$ 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!)
  $\rightarrow$ 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?
  $\rightarrow$ 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,

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

with τ = "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
  $\rightarrow$ convert energy to heat (thermal atom motion)
  $\rightarrow$ keep $T_{\rm surf}$ hot, replentish radiated energy
- then see how long each source could light up the Sun
- important source(s) $\equiv$ long-lived:
  $\tau_{\rm source} = E_{\rm res}/L_\odot > \tau_\odot = 5$ billion yr

Possible Solar Energy Sources

- Gravity

if Sun contracts $\rightarrow$ release grav. P.E.

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

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

- Chemical Energy

if entire Sun interior made of TNT (!)

burning $\rightarrow$ release chemical energy $\rightarrow$ heat

but: $\tau_{\rm chem} = 20{,}000$ years! yikes!

- Rotational Energy

Sun spins, has rotional energy

(rotational equivalent of kinetic energy)

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

if made Sun spin down (somehow)

convert spin energy to heat

but: $\tau_{\rm rot} \approx 400$ 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?"
$\rightarrow$ the power of (and necessity of) number crunching!

Nuclear Fusion in the Sun

The Sun is a nuclear reactor
i.e., nuclear reactions occur inside the Sun
change reactant nuclei into different product nuclei
$\rightarrow$ elements transformed into other elements
$\rightarrow$ cosmic alchemy!

Mechanism: high-energy/high-speed collisions between nuclei

$$\text{nucleus}_1 + \text{nucleus}_2 \rightarrow \text{nucleus}_3 + \text{energy} \qquad (3)$$

- nuke energy release $\rightarrow$ stellar power source
- lighter nuclei combine $\rightarrow$ heavier: **fusion**

Q: why are high energies, speeds needed?
Q: how do the nuclei have these energies & speeds?

In fact: many reactions can and do occur
but a small handful are the most important

Key reactions occur in "chains"

- first step involves pre-existing solar ingredients (*Q: namely?*)
- input for each new step is output from previous step

Dominant reactions: "pp" Chain

$$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu$$

$$e^- + e^+ \rightarrow \gamma + \gamma$$

$${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$$

$${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$$

Net effect:

$$4p + 2e^- \rightarrow \boxed{2n2p} = {}^4\mathrm{He} + \text{energy} + \ldots$$

each "p–p reaction" creates:

- ^{2}H=$\boxed{np}$ **"deuterium"**

"heavy hydrogen"

- e^+ **"positron"**

antimatter: anti-electron!

then $e^- + e^+ \rightarrow \gamma + \gamma$ energy!

annihilation

- ν **"neutrino"**

very low-mass ($m_\nu \ll m_e$) particle

only created in nuclear reactions ("weak" decays)

very weakly interacting particle

once born, go thru Sun, Earth, your body

but almost never interact

ν escape diagram