Astro 350

Lecture 16

February 23, 2022

Announcements:

- Good news: now homework or discussion this week
- Bad news: **Midterm exam in class this Friday**
- exam review at end of class today
- also office hours after class and by appointment

Last time: the nuclear powered Sun

Q: how do we know the Sun is nuclear powered?

Q: what is the main result of nuclear "burning" in the Sun?

Q: what's deuterium? a positron? a neutrino?

Only nuclear energy can allow the Sun (and other stars)
to burn for billions of years (age of Solar system, and Universe)

nuclear reactions in the Sun: **hydrogen 'burning'**
net effect: *nuclear reaction transform hydrogen → helium*
$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu$
nuke reactions taking light nuclei → heavier nuclei: **fusion**

first step in Solar reaction chain: $p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu$

- ${}^2\mathrm{H}$ = deuterium: heavy version (isotope) of hydrogen
- e^+ = positron: antimatter partner of electron
- ν = neutrino: ghostly, low-mass, weakly interacting particle
  only produced in (some) nuclear reactions
  and always present in proton ↔ neutron transformation
  for experts: this is an electron-type neutrino ν_e

Q: how can we observe neutrinos from the Sun?

In Search of Solar Neutrinos

experiments have been built to "see" solar neutrinos
by observing rare cases of ν interactions with atoms
all use huge underground detectors
Q: why huge? why underground?

Two types:
1. "radiochemical" – vats of fluid
see element change due to ν
ex: chlorine fluid $\nu + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$
collect Ar atoms (radioactive!)
`www: Davis chlorine experiment`

2. "scattering" – vats of ultrapure water
see light pulses from
high-energy e^- scattered by νs
`www: SNO ball`
`www: Super-K Sun image`

Solar Neutrino Experiments: Results

- ⋆ All experiments detect solar νs!
- ⋆ Scattering experiments show neutrinos come from the Sun!
- ⋆ Amount (neutrino flux) is just as predicted!

Q: what fundamental facts does this confirm?

Solar Neutrino Results

I. proof that Sun powered by nuke fusion

II. νs give view into solar core

III. these huge instrumented vats are ν telescopes!

A new window on the Universe:

Nobel Prize 2002!

Using the Sun to probe neutrino properties:

(flavor transformation and mass)

Nobel Prize 2015!

Cosmic Gall

by John Updike

Telephone Poles and Other Poems

1963

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.

The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall.

And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.

At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed–you call
It wonderful; I call it crass.

Cosmic Gall

by John Updike

Telephone Poles and Other Poems

1963 + 2019 Update!

Neutrinos, they are very small.
They have no charge and ~~have no~~ tiny mass
And ~~do not~~ hardly interact at all.

The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall.

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The Nuclear Powered Sun: Lessons

Imagine: a time machine takes you 100 years ago

you try to explain that the Sun and all stars:

- constantly create vast numbers of tiny invisible particles
- that pass through us all the time
- and are essential byproducts of the working of stars

Q: a lesson for cosmology?

The Stars as Suns

We've proved that Sun is nuclear reactor
but we've seen the Sun is a typical star
  typical mass, typical luminosity
$\Rightarrow$ **all** stars run by thermonuclear fusion

The Night sky, the Universe lit up ultimately by nuclear power

Poll: Stellar Life Expectancy

Vote your conscience!

What's the connection between how/high mass star lifespans?

A high mass $\rightarrow$ more fuel $\rightarrow$ burn longer

B low mass $\rightarrow$ low luminosity $\rightarrow$ burn longer

C more fuel $\rightarrow$ more luminosity $\rightarrow$ same lifespans for all stars

Life Expectancies of Stars

recall "flashlight equation" – energy conservation & star lifetime
(battery) = (wattage) × (lifetime) $\rightarrow$ $E_{\rm fuel} = L\tau$
for stars:

- more mass $\rightarrow$ stronger gravity $\rightarrow$ much hotter burn: $L \propto M^4$

`www: star luminosity data`

so if $M = 2M_\odot$, then $L = 16L_\odot$!

- fuel is mass, so $E_{\rm fuel} \propto M$

$\Rightarrow$ together this means

$$\tau = \frac{E_{\rm fuel}}{L} \propto M^{-3} \quad (1)$$

$$= 10 \text{ billion years } \left(\frac{M_\odot}{M}\right)^3 \quad (2)$$

example: lifespan $\tau(2M_\odot) = \tau_\odot/8 = 1.25$ billion years

so if a bunch of stars are formed with a range of masses
Q: what happens?

trend:

high mass $M \leftrightarrow$ high wattage $L \leftrightarrow$ short lifespan τ

e.g., massive star lifespans = few million years

low $M \leftrightarrow$ low wattage $\leftrightarrow$ long life

e.g., low-mass star lifespans = many billions of years

if many stars born at once–as in a cluster–then
massive stars die first (explode)
then only lower-mass stars left

observed! young cluster have massive stars
old clusters do not

Midterm Exam Review

Midterm Exam Info and Review

Exam info is Canvas:

Update–one page of handwritten notes allowed

Read & follow instructions for your Online Exam Setup

- need both a computer and a smartphone
- let me know if this setup will be a problem for you

Sample questions posted

Questions?