Astro 350
Lecture 11
Sept. 24, 2012

Announcements:

- good news: no HW next week
  bad news: **Hour Exam 1** Friday; info online
- *Discussion 4* due Wednesday
- *Bonus Participation*: class portrait on Compass
  identify yourself to help me learn your name

Cosmo-Bigshot today!

⋆ **Monday Sept 24**: Prof. Wick Haxton, U. California Berkeley
"The Origin of the Elements"
Phi Beta Kappa Lecture, 4pm Lincoln Hall 1090

Last time: cold gas as dark matter?

Q: why is cold gas a good DM candidate? how cold?

Q: how to test for cold gas DM? results? lessons?

Recap: Cold Gas as Dark Matter?

cold gas?

- has mass, but
- glows with thermal (blackbody) radiation
  but: if very cold, $T \ll 3,000$ K, peak λ is IR or radio
  even better: blackbody emission $\propto T^4$: low $T \Rightarrow$ dim!
  thermal radiation will be hidden

But: can use optical (or even UV) light from *other* galaxies

- passes through halo of host galaxy
- and through halo of our Galaxy
- if cold gas: should show up via absorption lines
- but: no such lines seen

$\Rightarrow$ the *majority of dark matter is* not *cold gas*! mystery remains!

Lineup of Dark Matter Suspects

~~hot gas~~

~~cold gas~~

black holes
neutron stars
white dwarfs
"failed stars" – "Jupiters," brown dwarfs

} compact objects

neutrinos

relic particles from big bang

Next candidates: compact objects

→ all arise from *birth and death* of *stars*

Stars and Cosmology

The Facts of Life for Stars

Fact: stars constantly radiates energy
and at a huge rate!
the Sun: a lightbulb with wattage $L_\odot = 4 \times 10^{26}$ 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?

Star Lives and the Consequences of Energy Conservation

the Sun and all stars:

- are constantly releasing energy to the rest of the universe, and
- require fuel, and are unable to "refuel" out of nothing, and
- thus must eventually run of out fuel

Thus:

- all stars – including the Sun – must eventually "burn out"
  = run out of fuel: *all stars are doomed to die*
  Q: important followup question?
- stars do not live forever

And thus:

- stars alive today were not alive forever
- *all stars must be born* as well as die

stars have life cycles

The Stability of the Sun

the Sun maintains the same size

at least over human timescales

→ don't consult weather for daily Sun growth or shrinkage

but because Sun keeps same size

→ surface at rest

→ not accelerating

→ no *net* force

but the Sun definitely has mass & gravity

so every part of the Sun attracts every other part of the Sun

result is inward force on itself

Q: but the Sun does not collapse—what's going on?

Preventing Death By Black Hole

if gravity were the only force on the Sun
entire Sun in *free fall*!
$\rightarrow$ all matter pulled to center
$\rightarrow$ collapse to a black hole!

but this obviously is false! the Sun and stars do exist!
and are stable – Sun doesn't shrink daily!

must be another force acting outward: **gas pressure**

Atoms, Gasses, Pressure, and Temperature

Take microscopic view of gas: what's going on with atoms?
in any gas (stars, Universe, this room):

- atoms widely spread $\rightarrow$ empty space between
- *constantly in motion* as free bodies until collision with other gas particles
- collisions "scramble"/randomize motion direction and tend to equalize particle energies

Now zoom back to our macroscopic view:

- enclosed gas exerts force–pressure–on walls
  Q: how does atom picture explain this?
- *Q: how does gas change if turn up T? what are atoms doing?*

Gas Pressure

atom bombardment exerts force (transfers linear momentum)
e.g., atoms collide with piston, push it outward
this leads to outward pressure force
$\rightarrow$ have to overcome this to compress gas
`www: simulation: gas & piston`

Gas Temperature

temperature T is a measure of average atom speed
more precisely: $T \propto$ average atom energy
for experts: ideal nonrelativistic gas has $kT = \frac{2}{3}\langle E \rangle = \frac{1}{3} m \langle v^2 \rangle$
$\rightarrow$ hotter gas $\rightarrow$ faster particles
$\rightarrow$ faster particles $\rightarrow$ higher pressure: $P \propto T$!

Q: so how does gas pressure affect star birth?

Star Birth: The Quest for Stability

cold gas clouds have small T $\rightarrow$ small pressure
$\rightarrow$ initially, pressure forces small
$\rightarrow$ gravitational collapse is (nearly) free fall

but *compression* $\rightarrow$ *heating*
as cloud collapses, pressure rises
until pressure forces as strong as gravity

eventually, star stabilized by becoming hot
inward gravity balanced by outward pressure
"hydrostatic equilibrium"

newborn stars remain stable as long as equilibrium maintained
$\rightarrow$ have to keep *hot* to maintain pressure

iClicker Poll: Cooling the Sun

Imagine a future industrial accident ("mistakes were made")
the Sun is robbed of much of its heat

What would happen if the Sun cooled off?

A the Sun would expand

B the Sun would shrink

C the Sun would remain the same size
but its atoms would have less random motion

Solar Cooling Simulation: Balloon

Q: Why is a balloon like the Sun? hint: forces & motion

cool by adding liquid nitrogen
$T < T_{\text{boil}} = -196°\text{C} = -321°\text{F} = 77\ \text{K}$

Q: what does this tell us about the Sun?
hint: compare the Sun and a cup of coffee?

Star Lifespans and Energy Sources

to fight gravity and be stable
the Sun must remain pressurized $\to$ must remain *hot*
and it does! Sun's T does not change (on human timescales)

but this is strange!
a cup of coffee starts out hot, but cools
  that is, loses heat energy to its environment
yet even though Sun emits energy too, at huge rate L
  still remains hot $\to$ needs *heat source = energy source*

To maintain luminosity (power output) L

for a *lifespan* τ

a star emits energy $E_{\text{emit}} = L\tau$

but energy conserved: fuel supply must be $E_{\text{fuel}} = E_{\text{emit}} = L\tau$

but since E_{fuel} finite, lifespan $\tau = E/L$ finite

$\rightarrow$ fuel will run out $\rightarrow$ all stars will die!

But what is fuel?

What form of energy in Sun is converted to light & heat?

Q: list all forms of energy in Sun?

Q: how can you tell which is the fuel supply?

we know (from radioactive dating) that

Sun lifetime $\tau_\odot >$ Solar System age $=$ 4.6 billon years

But: this requires enormous fuel supply $E_{\text{fuel},\odot} = L_\odot \tau_\odot$

Compare possible Solar energy sources:

- rotational energy (spin down, release KE):
  $\tau_{\text{rot}} = 100$ yr
- chemical energy (make entire Sun from TNT!):
  $\tau_{\text{chem}} = 20,000$ yr
- gravitational energy (contract $\rightarrow$release grav PE)
  $\tau_{\text{grav}} = 20$ million years $= 0.02$ billion years

Q: implications?

Cosmic Nuclear Reactors

Sun needs huge energy supply–a mystery until 1920's
→ nuclear energy discovered, only source that comes close
→ the Sun is a nuclear reactor!
→ all stars are nuclear reactors!

Mechanism: high-energy collisions

$$\text{nucleus}_1 + \text{nucleus}_2 \rightarrow \text{nucleus}_3 + \text{energy} \tag{1}$$

- nuke energy release → stellar power source
- lighter nuclei combine → heavier: fusion
  changes elements → stellar alchemy

To work: need high-energy collisions

- in lab: particle accelerator
- *Q: what about in stars?*

Nuclear Reactions in Stars–and the Universe!

macroscopic temperature $\leftrightarrow$ microscopic atom/particle motion
hotter $\rightarrow$ faster particles, collisions more frequent & energetic

Examples

- cooking food: heat $\rightarrow$ speed up chemical reactions $\rightarrow$ cooks!
- heat gas until particle energy $>$ electron binding to atoms
  e stripped away $\rightarrow$ gas of free e and ionized nuclei
  $\Rightarrow$ "plasma" – occurs for $T \gtrsim 10,000$ K
  $\Rightarrow$ star interiors and eary Universe are plasmas!
- heat a plasma until particle energy $>$ nuclear binding
  i.e., collision energy $>$ energy binding p and n together
  $\Rightarrow$ simulate particle accelerator conditions, get nuke reactions!
  need $T \gtrsim 10^7$ K = 10 million Kelvin