Astro 350

Lecture 34

Nov. 26, 2012

Announcements:

- **Homework 10** due Friday at start of class
- **Discussion 10** Wednesday

Before break: special topic–antimatter

Today: getting back in the flow

"running the movie backward" into the cosmic past

Q: ordinary matter behavior–cold to hot?

Q: implications for cosmic evolution?

Q: how's this working for us?

Cold Hot

atoms $\rightarrow$ ions=e+nuclei $\rightarrow$ $n + p + e$ $\rightarrow$ quarks $\rightarrow$???

As matter gets *hotter*
collisions *more violent*
ground to smaller bits

Universe should follow reverse trend: *cooling matter*:

Hot Cold

??? $\rightarrow$ quarks $\rightarrow$ $n + p + e$ $\rightarrow$ nuclei,e=plasma $\rightarrow$ atoms

the story so far:
ionized $\rightarrow$ *neutral* transition
also *opaque* $\rightarrow$ *transparent*
releases "fossil" radiation: CMB
$\rightarrow$ observed! has thermal spectrum! cosmic success story!

The Nuclear Force and Nuclear Structure

In nucleus:
Electrical repulsion between protons (like charges)
but stable: repulsion overcome by attractive force
nuclear force between p, n

nuclei are quantum objects governed by nuclear force
i.e., like "juiced" atoms, with stronger force

- still energy levels: ground, excited states
- stronger force $\rightarrow$ much much larger binding energy BE
  i.e., "sticking strength" $=$ energy input to rip apart
- still unbound if given energy $> BE$

The Ties that Bind

Nuclear force + quantum levels
$\rightarrow$ determines binding of each nucleus
`www: chart of nuclides`

weakest binding: deuterium $d =$ n+p

strongest binding in a light nucleus (below carbon):
^{4}He $=$ 2n+2p
^{4}He $= \alpha$ "alpha particle" tighly bound $=$ *very stable*
consequently, *no stable nuclei at mass 5, 8*
"would rather be alphas!"
mass 5 decays $\rightarrow \alpha + n$ or p
mass 8 decays $\rightarrow 2\alpha$

Cosmic Lingo: Fancy Name for Ordinary

neutrons and protons are not elementary
$\rightarrow$ both made of 3 quarks
other 3-quark particles exist, but are unstable
$\rightarrow$ decay to n or p

any particle made of 3 quarks: **baryon**
`www: lists of known baryons`

in practice: under most conditions, baryons = n or p
or things made of n and p: atoms, people, stars, galaxies

so: to cosmologists
baryons = "made of atoms" "ordinary" matter $\neq$ dark matter

Primordial Nucleosynthesis

Primordial nucleosynthesis, a.k.a. Big bang nucleosynthesis (BBN):
production of lightest elements H, He, Li
in the early U.

extrapolate expanding U, containing matter, radiation
back to $t \sim 1$ sec $\rightarrow$ U is giant nuke reactor!

basic story:
transition from "ionized" free n and p
to "neutral" bound nuclei, largely ^{4}He

Q: at high (but not ultrahigh) T, what are cosmic ingredients?

Primordial Nucleosynthesis Initial Conditions

time $t < 1$ sec, temperature $T > 10^{10}$ K $=$ 10 billion degrees

radiation

- "CMB" photons now gamma rays!
- also a sea of cosmic neutrinos!

radiation density huge!

$\rightarrow \rho_{\text{radiation}} \gg \rho_{\text{matter}}$ opposite of situation today
"radiation-dominated era"

matter

- ordinary (known) matter: only n, p, and e
  collisions too violent for complex nuclei
  and certainly much too violent for atoms
- dark matter: must be around, but weakly interacting

dark energy

must also be around, but if Λ-like, unimportant

iClicker Poll: Cosmic Fusion

primordial nuke: transition from free n, p
to bound nuclei, through a series (chain) of reactions

Starting from p and n only, which nucleus is made first?

A deuterium: $d = \boxed{np}$

B helium-3: $^3\text{He} = \boxed{npp}$

C helium-4: $^4\text{He} = \boxed{nnpp}$

∞ **D** lithium-7: $^7\text{Li} = \boxed{3p, 4n}$

Primordial Nucleosynthesis: Element Production

as the universe expands and cools,
n and p collisions weaker than $d = \boxed{np}$ binding
$\rightarrow$ at last d can survive: $n + p \rightarrow d$
then can combine d with n, p, and d to make heavier things
`www: reaction network`

flow $\rightarrow$ most stable (tightest binding) = $\boxed{{}^4\text{He}}$
essentially all $n \rightarrow {}^4$He
BBN result: 25% of baryons in He, leftover $p \rightarrow$ H (75%)
small traces of unburnt D, ^{3}He, ^{7}Li:
amounts depend strongly on density of nuclei ("*baryons*")
`www: Schramm plot`

Nothing heavier than lithium made–why?

Nuclear Freeze

nothing heavier than Li:

- no stable nuclei with masses $5, 8$
  $\Rightarrow$ don't make anything from $p + {}^4$He or ^{4}He $+ {}^4$He

- cooling universe $\rightarrow$ weaker collisions
  but combining nuclei with large charge
  requires large energy to overcome electrical repulsion

result: nuclear reactions shut down after lithium production
...and not even much of that!
"freezeout of strong interactions"

BBN Predictions: Executive Summary

Q: what are main predictions? qualitatively, quantitatively?

Q: where, when do they apply?

Q: what predictions "robust"/unavoidable?

Q: what would be involved in testing the predictions?

Q: what would it mean if BBN predictions confirmed? if not?

Q: what assumptions went into the calculation? ("Standard BBN")

Q: i.e., regarding dark matter? dark energy? neutrinos? additional element ary particles?