Astro 406

Lecture 36

Dec. 2, 2013

Announcements:

- **PS 12 due Friday** last problem set!
- **ICES** is online, available now
  I do read your comments and use them
  please take a moment and help future generations

Before break: cosmic nuclear age–big bang nucleosynthesis (BBN)

Q: when? what is U like then?

Q: what happens?

Q: what fossil(s) are left?

iClicker Poll: ICES

Have you received the ICES email?

A yes, and I promise to go to www: `https://ices.cte.uiuc.edu` and fill out the form for this course

B no, but anyway I promise to go to www: `https://ices.cte.uiuc.edu` and fill out the form for this course

Primordial Nucleosynthesis

production of lightest elements H, He, Li in the early U.

transition in baryon states:
from "ionized" free n and p to bound nuclei

BBN results:
`www: Schramm plot`

⋆ early universe makes mostly H and He

- $Y_p = \rho(^4\text{He})/\rho_{\text{baryon}} = 25\%$ of baryons in ^{4}He
- leftover $p \rightarrow$ H (75%)

⋆ large ^{4}He abundance inevitable
Y_p nearly independent of $\eta = n_{\text{baryon}}/n_\gamma$
$\Rightarrow$ test of the big bang: U. better have lotsa ^{4}He!

BBN: Observations

to test BBN: measure primordial abundances

look around the room–not 75% H, 25% He.
Q: is this a problem? Why not?

matter in solar system: mostly in Sun–mostly H, then He
but: still have heavy elements
Q: is this a problem? Why not?

Q: so how test BBN? What is the key practical issue?
Q: when in cosmic history do we expect
the first "complications"?

BBN theory: universal composition after ~ 3 minutes, $z \sim 10^9$
observations: abundances in real astro systems, redshifts $z \sim few$

the first non-BBN nucleosynthetic processing:
$\rightarrow$ when first stars turn on
`www: circle of life`

problem: stars change lite element abundances $\rightarrow$ "pollution"

the solution:
Q: how to address this problem?
Q: if can measure abundances in a system, can you unambiguously tell that stars have done some polluting?
Q: how to tell observationally which systems least polluted?

The Solution to Pollution

stars also make heavy elements

stellar cycling: metals $\leftrightarrow$ time

measure both **light elements** and **metals**
low metallicity $\rightarrow$ more primitive
as metals $\rightarrow 0$: *primordial*

Will illustrate with two examples:
^{4}He and deuterium

Helium-4

He atoms: high ionization potential
$\Rightarrow$ need hot H II region

hot, low metals $\rightarrow$ "extragalactic H II region"
metal-poor, dwarf irregular galaxies
`www: I Zw 18`

measure via nebular lines *Q: emission or absorption?*
`www: observed He line`

$Y = \rho(^4\text{He})/\rho_{\text{baryon}}$ and $Z = \rho(\text{metals})/\rho_{\text{baryon}}$
$\Rightarrow$ correlated
What correlation do you expect?

Transp: Y *vs* Z
Q: significance of features?

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measure via nebular emission lines
Transp: *He line*

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∞

Transp: Y *vs* Z
Q: significance of features?

Helium-4 Data: Trends and Implications

Data best fit by

$$Y = Y(Z) \simeq Y_0 + \frac{\Delta Y}{\Delta Z}\, Z \tag{1}$$

slope $\Delta Y / \Delta Z$: stellar nuke
    (avg stellar "helium per metal" output)
intercept $Y_0 = Y_p$: cosmology (primordial He!)

world average (BDF & Olive 99):

$$Y_p = 0.249 \pm 0.009 \tag{2}$$

Deuterium

measure D/H at high z

in "quasar absorption line systems" *Q: what's a quasar?*

for our purposes: QSO = high-z continuum source (lightbulb)

`www: QSO spectrum`

consider cloud, mostly H at $z < z_{\rm qso}$, but still high z

e.g., $z_{\rm qso} = 3.4, z_{\rm cloud} = 3$

• H absorbs γ if energy tuned to levels

lowest: $n = 1 \to 2$, Lyα **Transp:** *H energy levels*

• but Lyα in QSO frame redshifted in cloud frame

What happens?

What about a cloud at yet lower z?

for a cloud at $0 < z < z_{\rm QSO}$:
a photon that *was* tuned to Lyα at QSO
now redshifted *out* of resonance
but a photon that was too high-E
has now been redshifted *into* resonance!
a absorption line created at $\lambda < \lambda_{{\rm Ly}\alpha,{\rm QSO}}$

more clouds: lather, rinse, repeat:
intervening material seen via absorption
H: "Lyman-α forest"
`www: QSO spectrum`

That was for all H, mostly ^{1}H$=p$
but what about deuterium?
D: energy levels slightly shifted from H
can show $\Delta\lambda/\lambda = -1/2\ m_e/m_p$
$c\Delta\lambda/\lambda = -82$ km/s
look for "thumbprint"
sketch diagram: Flux vs λ

Deuterium Results

For the 6 best systems
(clean D, well-determined H)

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.84 \pm 0.26) \times 10^{-5} \tag{3}$$

For the top 2 (multiple transitions)

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.49 \pm 0.18) \times 10^{-5} \tag{4}$$

Assessing BBN: Theory vs Observations

BBN Theory:
Transp: *Schramm plot*

all element abundances dependent on η
the only free parameter in standard ("vanilla") calculation
$\Rightarrow$ for each η value, 4 light elements

Q: at any moment, how many values of η in Universe?

Q: what do we learn if we measure one light element?
Q: and then if we measure more?

the universe is homogeneous:
at any time, each of n_{baryon}, n_γ, and $\eta = n_{\text{baryon}}/n_\gamma$
has a single value

BBN theory predicts primordial abundances
i.e., determines $y_i^{\text{theory}}(\eta)$ for $i \in$ D, ^{3}He, ^{4}He, ^{7}Li

Lite Element Observations:
measure 1 element abundance y_i^{obs}
- set $y_i^{\text{obs}} = y_i^{\text{theory}}(\eta)$
- determine η! really, a range of η

Q: Why a range?

then measure another element
- same procedure independently finds its own range in η
- compare! $\Rightarrow$ do they agree? test of BBN!

iClicker Poll: BBN Theory Meets Observations

Vote your conscience

Each of D, ^{4}He, and ^{7}Li "picks" a cosmic baryon density

Do these "votes" agree?

A yes–to high precision!

B yes–to within a factor of 2

C no–they are wildly off and something has gone wrong!

D too early to tell

Assessing BBN: Procedure

Combine observations *and their uncertainties**

Concordance!

`www:  Schramm plot w/ data boxes`

lite elements fit if η in range

$$5.7 \times 10^{-10} \leq \eta_{10} \leq 6.7 \times 10^{-10} \quad (5)$$

Have extrapolated hot big bang to $t \sim 1$ s
predict lite elements $\rightarrow$ agrees w/ thy
big bang model works back to $t \sim 1$ s, $z \sim 10^{10}$!
lends confidence to extrapolation $t < 1$ s

*For experts–*systematic* errors are dominant here (hardest kind to get right!)

BBN: Implications

recap: extrapolated big bang to $t = 1$ s, predicted lite elements
kinda amazing: not only qualitative agreement ("lotsa helium")
but even detailed quantitative agreement with observations!
Cosmo bragging rights: BBN is earliest probe!

What good is $\eta = n_B/n_\gamma$?
both n_B and n_γ change with time
But: $\eta = n_B/n_\gamma = const$ *Q:why?*

PS: given T_0, $\eta \propto \rho_{\rm baryon,0} \propto \Omega_{\rm B} h^2$
BBN (and $h = 0.73$):

$$0.042 \lesssim \Omega_{\rm B} \lesssim 0.050 \qquad (6)$$

Q: what stuff is included in $\Omega_{\rm B}$?
Q: to what should this number be compared?

BBN tells baryon density: *anything made of protons & neutrons*

$$0.042 \lesssim \Omega_\mathrm{B} \lesssim 0.050 \quad (7)$$

a quantitative result with big qualitative implications!

⋆ $\Omega_\mathrm{B} \ll 1$: baryons don't close the U.

⋆ From (optical) luminosity density $\mathcal{L}$
and stellar mass-to-light $\Upsilon_\star = (M/L)_\star \sim 1 M_\odot/L_\odot$
can get $\rho_\mathrm{lum} = \Upsilon_\star \mathcal{L}$ (and you did, in PS)
find: $\Omega_\mathrm{lum} \sim 0.007 \ll \Omega_\mathrm{B}$
most baryons not (optically) luminous!
baryonic dark matter
Q: where might they be hiding?

⋆ $\Omega_\mathrm{matter} \approx 0.3 \gg \Omega_\mathrm{B}$:
most matter not in baryons of any kind!
non-baryonic dark matter

Lineup of Dark Matter Suspects

~~hot gas~~

~~cold gas~~

~~black holes~~
~~neutron stars~~
~~white dwarfs~~
~~"failed stars" "Jupiters," brown dwarfs~~
} ~~compact objects~~

~~baryons in any form~~

neutrinos

exotic relic particles from big bang

Q: but recall PS11–what about neutrinos?

Lineup of Dark Matter Suspects: Final Summary

~~baryons in any form~~

~~neutrinos~~

exotic relic particles from big bang

We have exhausted the list of known particles
found in laboratories or accelerators
i.e., "the Standard Model of Particle Physics"

if dark matter is a particle at all
points to physics beyond the Standard Model!

or: Einstein and General Relativity are wrong!

Director's Cut Extras

Concordance Revisited

the above picture of concordance was oversimplified!

the modern picture uses the *CMB* to determine η
and then BBN theory predicts all light element abundances
and then we can compare each prediction with observations

we find:

- *deuterium* observation agreement with theory is spectacular!
- ^{4}He observation agreement with theory is *good*!
- ^{7}Li observation agreement is *poor*!
  this is the *cosmic lithium problem*

The Cosmic Lithium Problem

BBN theory (+CMB) predicts ^{7}Li/H a factor ~ 4 *higher*
than observed in ancient (metal-poor) Galactic halo stars

What could explain this?

- **stellar burning**

some stars (including the Sun!) have deep convective currents
and drag their surface matter to the interior
lithium can be burned this way

this could explain the problem but:
all stars show a large deficit
how could destruction be so uniform in different environments
and with different initial conditions?

• **new physics**

if something happened in the Early Universe during or after BBN
creating new particles and energy
or changing the dynamics of existing particles and energy
the ^{7}Li abundance could be changed

most popular example: dark matter decays during BBN

this could explain the problem but:
usually the new perturbations
not only change ^{7}Li, but also the other light elements
solutions exist, but have to be "fine-tuned" to keep from
driving D and ^{4}He out of concordance

either way, light elements teach us about dark matter!