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?

- Α
 - 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:

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www: Schramm plot

 \star early universe makes mostly H and He

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

\star large ⁴He abundance inevitable

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

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?

 $_{\sigma}$ 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: ⁴He 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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Helium-4

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He atoms: high ionization potential \Rightarrow need hot H II region
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hot, low metals \rightarrow "extragalactic H II region"
metal-poor, dwarf irregular galaxies
www: I Zw 18
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measure via nebular emission lines **Transp:** *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?
```

Helium-4 Data: Trends and Implications

Data best fit by

$$Y = Y(Z) \simeq \frac{Y_0}{\Delta Z} + \frac{\Delta Y}{\Delta Z} Z$$
 (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 zin "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 $z < z_{qso}$, but still high z

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

- H absorbs γ if energy tuned to levels lowest: $n = 1 \rightarrow 2$, Ly α Transp: H energy levels
- but $Ly\alpha$ in QSO frame redshifted in cloud frame *What happens?*

What about a cloud at yet lower z?

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for a cloud at 0 < z < z_{QSO}:
a photon that was tuned to Ly\alpha 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_{LY\alpha,QSO}
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more clouds: lather, rinse, repeat:
intervening material seen via absorption
H: "Lyman-\alpha forest"
www: QSO spectrum
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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 \ \text{km/s}
look for "thumbprint"
sketch diagram: Flux vs \lambda
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Deuterium Results

For the 6 best systems

(clean D, well-determined H)

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

For the top 2 (multiple transitions)

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

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 $n_{\rm baryon},~n_{\gamma},~{\rm and}~\eta=n_{\rm baryon}/n_{\gamma}$ has a single value

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

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

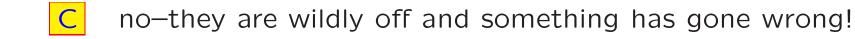
Each of D, ⁴He, and ⁷Li "picks" a cosmic baryon density

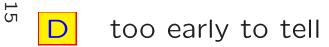
Do these "votes" agree?

A yes-to high precision!



yes-to within a factor of 2





Assessing BBN: Procedure

Combine observations *and their uncertainties** Concordance!

www: Schramm plot w/ data boxes

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lite elements fit if \eta in range
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$$5.7 imes 10^{-10} \le \eta_{10} \le 6.7 imes 10^{-10}$$

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

$0.042 \lesssim \Omega_{\mathsf{B}} \lesssim 0.050 \tag{6}$

 $\stackrel{r_{i}}{\sim}$ Q: what stuff is included in Ω_{B} ? Q: to what should this number be compared?

BBN tells baryon density: anything made of protons & neutrons

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

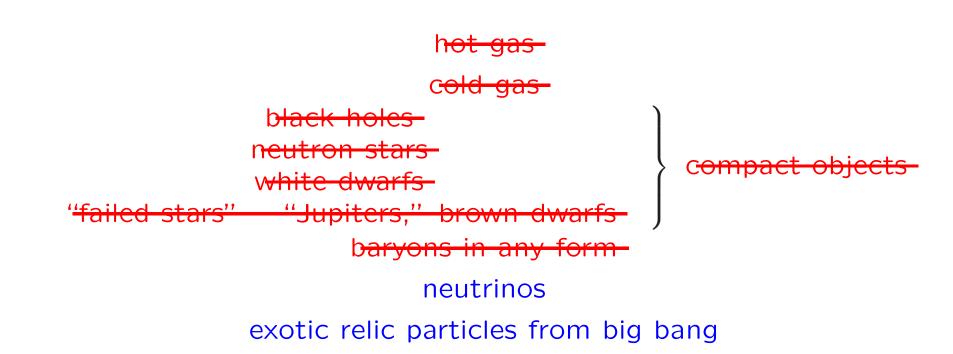
a quantitative result with big qualitative implications!

 \star Ω_B ≪ 1: baryons don't close the U.

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

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

Lineup of Dark Matter Suspects



□ 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!

20

or: Einstein and General Relativity are wrong!



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**!
- ⁴He observation agreement with theory is *good*!
- ⁷Li 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

 $\stackrel{\toppot}{\sim}$ 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 ⁷Li 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 ⁷Li, but also the other light elements solutions exist, but have to be "fine-tuned" to keep from driving D and ⁴He out of concordance

 $\stackrel{\aleph}{=}$ either way, light elements teach us about dark matter!