Chemical Evolution of the Universe

$$\rho_c = \frac{3H_0^2}{8\pi G} \qquad \Omega_i \equiv \frac{\rho_i}{\rho_c}$$

$$H_0 = 72\text{km/s/Mpc} = (4.3 \times 10^{17} s)^{-1} = (13.6 Gyr)^{-1}$$

$$\Omega_M \equiv 0.3 = 2.9 \times 10^{-30} g/cm^3$$

$$\rho_{CMB} = \frac{\frac{4}{c}\sigma T^4}{c^2} \qquad T = 2.73\,\text{K} \qquad \frac{\Omega_\gamma}{\Omega_M} = 1.6 \times 10^{-4}$$

$$\rho_{CMB} = 4.6 \times 10^{-34} g/cm^3$$

As we look back in time, photons have wavelengths shortened by (1+z)

$$B(\lambda/(1+z)) = B(T)$$

$$T_{CMB} = T_{CMB}^{z=0}(1+z)$$

$$\rho_M(z) = (1+z)^3\, \rho_M(z=0)$$

$$\rho_\gamma(z) = (1+z)^4\, \rho_\gamma(z=0)$$

$$\frac{\Omega_\gamma(z)}{\Omega_M(z)} = 1.6 \times 10^{-4}(1+z)$$

at z=6400, Universe becomes photon dominated…
T~17000K
At increasingly higher z, we can achieve any temperature we want

In the few minutes after the Big Bang, the initial Composition of the Big Bang is set by a series of nuclear reactions…

$$p + e \underset{\Lambda_{n\nu}}{\overset{\Lambda_{pe}}{\rightleftarrows}} n + \nu \qquad p + \bar{\nu} \underset{\Lambda_{ne+}}{\overset{\Lambda_{p\bar{\nu}}}{\rightleftarrows}} n + e^+$$

$$\frac{dn_n}{dt} = (\Lambda_{pe} + \Lambda_{n\nu})_{t_p} - (\Lambda_{p\bar{\nu}} + \Lambda_{ne+})_{t_n}$$

$$\text{for } T > 10^{10.14} \quad \Lambda_{pe} = \Lambda_{n\nu} = \Lambda_{p\bar{\nu}} = \Lambda_{ne+} \propto (T^{-5}) \qquad T = 10^{10.125} t^{-1/2} s$$

$$\nu + \bar{\nu} \Leftrightarrow e^+ + e \quad \text{for } T > 10^{10.5}$$

$$e^+ + e \Rightarrow \gamma + \gamma$$

So at T>$10^{10.5}$ (t < 0.2s) $p + e \underset{\Lambda_{n\nu}}{\overset{\Lambda_{pe}}{\rightleftarrows}} n + \nu \qquad p + \bar{\nu} \underset{\Lambda_{ne+}}{\overset{\Lambda_{p\bar{\nu}}}{\rightleftarrows}} n + e^+$

at T=$10^{10.5}$ (t = 0.2s) $\nu + \bar{\nu} \Leftrightarrow e^+ + e$ for $T > 10^{10.5}$

So at T~$10^{10.14}$ (t < 0.9s) $e^+ + e \Rightarrow \gamma + \gamma$

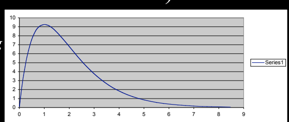
End up with mainly protons, neutrons and electrons (some neutrinos) when Universe is 1 second old
With ratio of N/P set as $e^{-\Delta E_{binding}/kT_{decoupling}} \approx 1/e$

$$\frac{n_n}{n_p} = e^{-\Delta E_{binding}/kT_{decoupling}}$$

$$\Delta E_{binding} = 1.293 MeV (\text{Neutron - Proton})$$

$$\text{kT}_{decoupling} \approx 0.5 \Delta E_{binding}$$

$$\frac{n_n}{n_p} \approx e^{-2} = 0.14$$



In Subsequent reactions (200s worth), almost all neutron end up in He-4. Except those neutrons that decay … So if 1/7th of all nucleons are a neutron, and Helium-4 has equal numbers of neutrons and protons…then 2/7th of all nucleons will end up in He-4 - or 28% of the mass of the Universe…A bit less 28%*exp(-100s/900s) =24% when one takes into account neutron decay…

$n \overset{t_{1/2}=887s}{\Rightarrow} p + e + \bar{\nu}$ Neutrons decay with half-life of 887 seconds

$n + p \Leftrightarrow D + \gamma$ Formation/Destruction of Deuterium

$T = 10^{8.9}\text{K} \;\; n_D > n_n$ Neutrons converted to D at roughly 200s From Saha equation (but Neutron Decay!, etc)

$$d + n \text{ ® } H^3 + \gamma$$

$$H^3 + p \text{ ® } He^4 + \gamma$$

$$D + p \text{ ® } He^3 + \gamma$$

$$He^3 + n \text{ ® } He^4 + \gamma$$

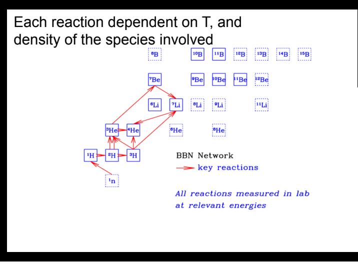
$$D + D \text{ ® } He^3 + n$$

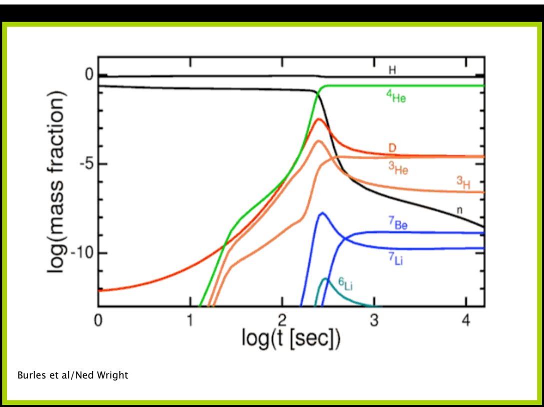
$$D + D \text{ ® } H^3 + p$$

$$H^3 + D \text{ ® } He^4 + n$$

$$He^3 + D \text{ ® } He^4 + p$$

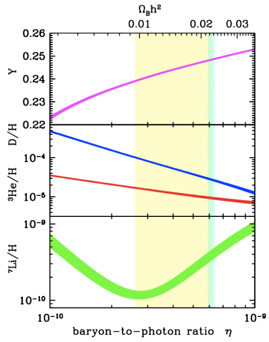
$$D + D \text{ ® } He^4 + \gamma$$





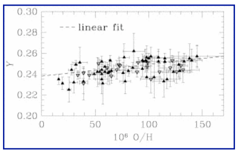
Burles et al/Ned Wright

Prediction of BBN



Measuring He abundance

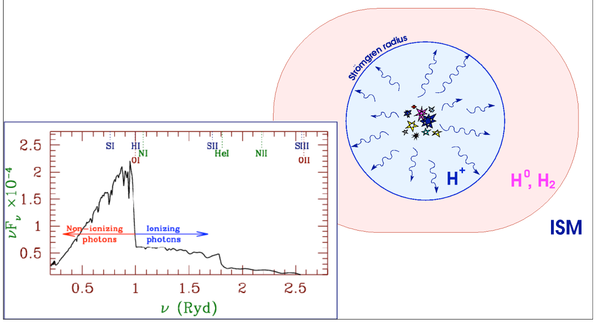
$$Y \equiv \frac{\rho_{He}^{primordial}}{\rho_{H}^{primordial}}$$



(Fields & Olive 1998, ApJ 506, 177)

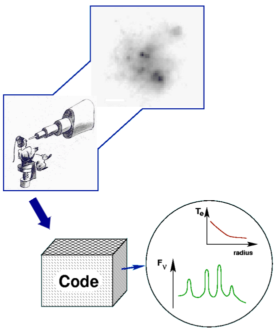
➡

H II regions are gas clouds ionized by young, massive stars



There are several ways to deal with the uncertainty associated to the ionization structure

1. applying selection criteria
2. building tailored photoionization models
3. using narrow-slit data



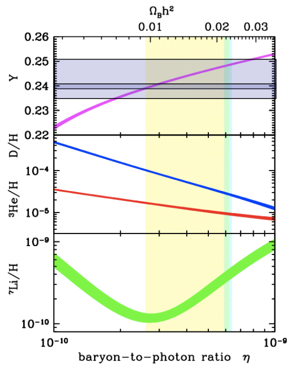
Historical Problems amd their solutions

	problem	solution
physics	atomic parameters	Hope Physics has this right
stellar parameters	stellar absorption	stellar libraries
	ionization structure	tailored models
nebular parameters	temperature structure	self-consistent solution
	H I collisions	Better Modeling, especially at low Z

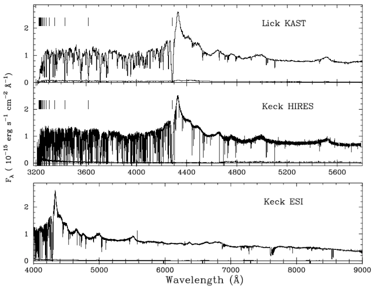
Two Recent Results

Source	$Y_{Primordial}$
Izotov et al. 1999	0.2452±0.0015±0.0070
Peimbert et al. 2002	0.2391±0.0020±0.0010

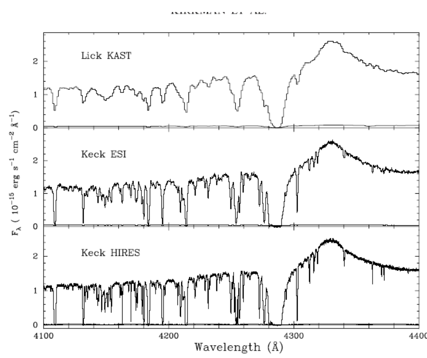
Hoyle & Tayler 1964
Peebles 1966
Searle & Sargent 1972
Peimbert & Torres−Peimbert 1974
Peimbert & Torres−Peimbert 1976
D Odorico et al. 1976
Lequeux et al. 1979
French 1980
Kunth & Sargent 1983
Peimbert 1985
Pagel et al. 1986
Kunth 1986
Pagel 1987
Steigman 1987
Torres−Peimbert et al. 1989
Pagel & Simonson 1989
Melnick et al. 1992
Pagel et al. 1992
Mathews et al. 1993
Mathews et al. 1993
Skillman & Kennicutt 1993
Izotov et al. 1994
Olive & Steigman 1995
Sasselov & Goldwirth 1995
Izotov et al. 1997
Hogan et al. 1997
Izotov & Thuan 1998
Izotov et al. 1999
Viegas et al. 2000
Ballantyne et al. 2000
Peimbert et al. 2000
Peimbert et al. 2001
Peimbert et al. 2002
Gruenwald et al. 2002
Luridiana et al. 2003

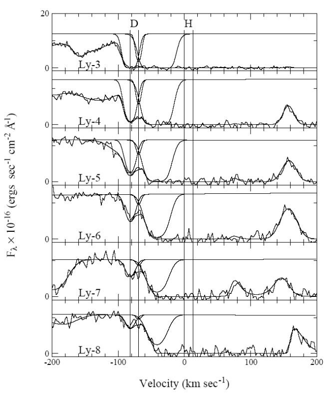


Measure D/H Ratio



QSO at z=2.6 from Kirkman et al





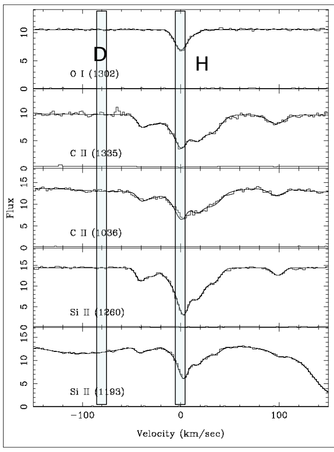
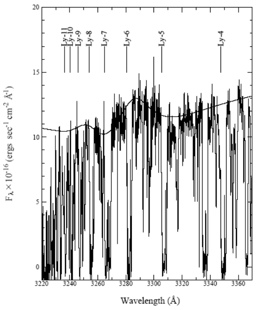


TABLE 3
IONS IN THE $z \simeq 2.526$ ABSORPTION SYSTEM TOWARD Q1243+3047

Ion	log N (cm^{-2})	b^a (km s^{-1})	z	v (km s^{-1})
H I total[b]	19.73 ± 0.04	...	...	...
H I (H-3)	15.90 ± 0.03	17.0 ± 1.0	2.525171	−44.3 ± 7.0
H I (H-1)	19.63	14.8 ± 2.9	2.525659	−2.8
H I (H-2)	19.05	10.9 ± 3.3	2.525804	9.5
H I (H-4)	16.25 ± 0.02	25.8 ± 0.9	2.526939	106.0 ± 0.7
H I (H-5)	16.35 ± 0.02	26.6 ± 0.5	2.528108	205.4 ± 0.3
D I total........	$15.113^{+0.042}_{-0.026}$	...	...	...
D I (D-1)	15.058 ± 0.03	9.2 ± 0.2	2.525659	−2.8 ± 0.6
D I (D-2)	14.191 ± 0.10	<12	2.525804	$9.2^{+2}_{-3.5}$
O I (O-1)[c].......	13.570	6.766	2.525692	0.0[d]
O I (O-2)[c].......	12.755	6.766	2.525848	13.3[d]
Si II..............	11.884	3.44	2.525209	−41.0
Si II..............	11.783	5.89	2.525342	−29.8
Si II..............	12.020	7.85	2.525568	−10.5
Si II..............	11.830	3.76	2.525635	−4.8[d]
Si II..............	12.766	4.46	2.525728	3.1[d]
Si II..............	12.473	5.99	2.525885	16.4[d]
Si II..............	11.508	3.27	2.525984	24.8
Si II..............	12.120	7.41	2.526083	33.3
Si II..............	11.751	5.97	2.526856	99.0
C II..............	12.521	3.03	2.525215	−40.5
C II..............	12.987	11.06	2.525324	−31.2
C II..............	12.693	9.97	2.525552	−11.9
C II..............	12.956	7.58	2.525626	−5.6
C II..............	13.344	5.21	2.525708	1.4[d]
C II..............	13.260	7.17	2.525872	15.4[d]
C II..............	12.921	12.73	2.525959	22.8
C II..............	13.150	10.40	2.526076	32.7
C II..............	12.916	10.59	2.526834	97.1
Al II[e]............	<12.2	7	...	0[d]
Si III[f]............	<13.0	7	...	0[d]
C IV[g]............	<12.75	7	...	0[d]
C II*............	<12.3	...	...	0
C IV..............	13.190	38.81	2.525750	4.9
C IV..............	13.256	20.98	2.526171	40.8
C IV..............	13.248	29.53	2.526985	110.0
C IV..............	12.514	14.11	2.528017	197.7
Si IV[g]............	<12.4	7	...	0[d]
Si IV..............	12.905	37.64	2.525560	−11.2
Si IV..............	12.730	17.21	2.526145	38.6
Si IV..............	12.709	24.33	2.526944	106.5
Si IV..............	11.920	10.71	2.527978	194.4



Continuum level

TABLE 5

D/H Measurements toward QSOs

QSO	z_{DH}	D/H ± 1 σ (×10^{-5})	log D/H	X_i[a]	b(D) (km s^{-1}) Predicted	b(D) (km s^{-1}) Observed
PKS 1937−1009[b]	3.572	3.25 ± 0.3	−4.49 ± 0.04	+1.65	12.5 ± 2.1[c]	14.0 ± 1.0
Q1009+299[d]	2.504	$3.98^{+0.59}_{-0.67}$	$-4.40^{+0.06}_{-0.08}$	+1.95	13.5 ± 0.5[c]	15.7 ± 2.1
HS 0105+1619[e]	2.536	2.54 ± 0.23	−4.596 ± 0.040	−1.00	10.1 ± 0.3[c]	9.85 ± 0.42
Q1243+3047[f]	2.525675	$2.42^{+0.35}_{-0.25}$	$-4.617^{+0.058}_{-0.048}$	−1.05	11.3 ± 1.8	9.2 ± 0.2
Q2206−199[g]	2.0762	1.65 ± 0.35[h]	$-4.78^{+0.08}_{-0.10}$	−2.80	10.6	…
Q0347−3819[i]	3.024855	3.75 ± 0.25[h]	−4.43 ± 0.03	+4.20	3, 14.1, 16.2	…
Q0130−403[j]	2.799	<6.8	<−4.17	…	16.2 ± 0.3[c]	…

[a] $X_i = (Y_i - \text{mean})/\sigma(Y_i)$, where $Y_i = \log(\text{D/H})_i$ and we use the weighted mean of the first five QSOs, log D/H = −4.556 ± 0.064.
[b] We list combined results for the two components, from Tytler et al. 1996 and Burles & Tytler 1998a.
[c] Calculated from the published data and first presented here.
[d] We list combined results for the two components, from Tytler & Burles 1997 and Burles & Tytler 1998b.
[e] O'Meara et al. 2001.
[f] This paper.
[g] Pettini & Bowen 2001.
[h] Discussed in the Appendices of this paper.
[i] First analyzed by D'Odorico et al. 2001. We qu
[j] From Kirkman et al. 2000.

TABLE 6

Column Densities and Metal Abundances where D/H is Measured

QSO	log $N_{\rm H\,I}$ (cm^{-2})	Element α	Abundance [α/H]
PKS 1937−1009[a]	17.86 ± 0.02	Si	−2.7, −1.9
Q1009+299[b]	17.39 ± 0.06	Si	−2.4, −2.7
HS 0105+1619[c]	19.422 ± 0.009	O[d]	−1.73
Q1243+3047[e]	19.73 ± 0.04	O[d]	−2.79 ± 0.05
Q2206−199[f]	20.436 ± 0.008	Si	−2.23[g]
Q0347−3819[h]	20.626 ± 0.005	Si	−1[i]
Q0130−403[j]	16.66 ± 0.02	Si	−2.6

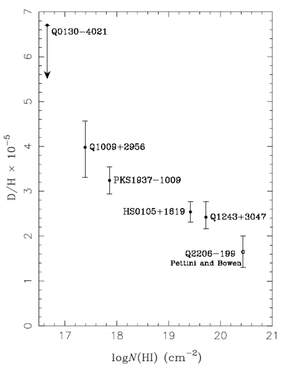
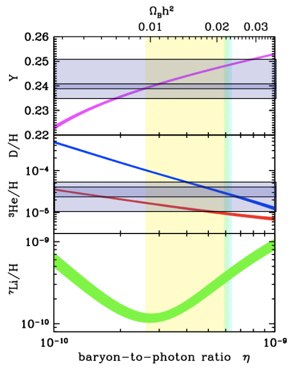


Fig. 21.—Same as Fig. 20, but showing D/H as a function of the H I column density. This correlation is unexpected, and we believe it is an accident.

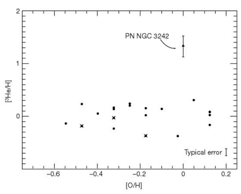
Line confusion

Stellar Processi



Measuring ^{3}He

- ^{3}He is processed by stars being created from Deuteurium but also burned into heavier elements. But ^{3}He seems to be constant as a function of metallicity for most stars



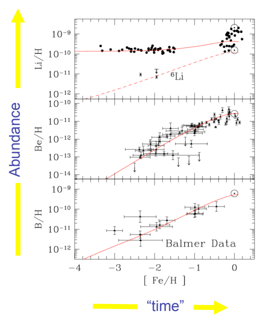
Relatively complex (and undeveloped model) suggests He3 Stays with stars most of the time, only 10% of time ejected – Therefore solar abundance is correct???? This is not uniformly accepted – generally agreed should not use He3

Measuring Lithium, Beryllium and Boron

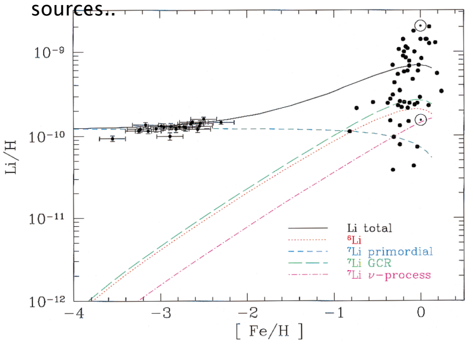
Observe in primitive (Pop II) stars
Li-Fe ⇨ evolution

- Plateau at low Fe Spite & Spite 82
  - ➢ const. abundance at early epochs
  - ➢ Li is primordial
- No plateau for Be and B:
  - ➢ Not primordial,
  - ➢ Made by Galactic process(es)

BBN Prediction: Thomas, Schramm, Olive, BDF 93
^{6}Li, Be, B unobservably small
Consistent with observations



Lithium does evolve slowly due to SN? Or other sources..



Choose stars without convective envelopes…
Measure…

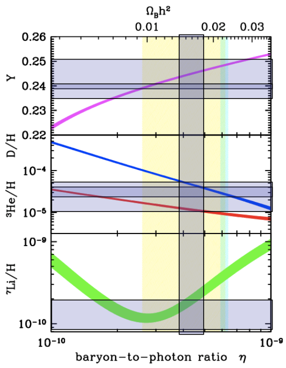
TABLE 1

INFERRED PRIMORDIAL LITHIUM ABUNDANCE: OBSERVED (RNB) ABUNDANCE IS $\langle A(\mathrm{Li})\rangle_{-2.8} = 2.12 \pm 0.02$

Corrections to Apply Logarithmically	Value	Estimated Uncertainty
(1) GCE/GCR:		
Previous analyses (RNB)	−0.14 to −0.05	
Log data fit (eq. [1])	−0.20 to −0.09	
Linear data fit (eq. [2])	−0.12 to −0.04	
Linear data fit (eq. [3])	−0.16 to −0.05	
Model fits (eqs. [2]–[3])	−0.05 to −0.04	
Adopted (excludes model)		$-0.11^{+0.07}_{-0.09}$
(2) Stellar depletion		$+0.02^{+0.08}_{-0.02}$
(3a) T_{eff}-scale zero point		+0.08 ± 0.08
(3b) One-dimensional atmosphere models		$+0.00^{+0.10}_{-0.00}$
(3c) Convective treatment		$+0.00^{+0.08}_{-0.00}$
(3d) Non-LTE		−0.02 ± 0.01
(3e) *gf*-values		+0.00 ± 0.04
(4) Anomalous objects		+0.00 ± 0.01
Total		$-0.03^{+0.19}_{-0.13}$
Inferred $A(\mathrm{Li}_p)$		$+2.09^{+0.19}_{-0.13}$

NOTE.—The weighted mean and 95% CL uncertainty of observed Li abundances for a very metal-poor sample of halo main-sequence turnoff stars (RNB) with $\langle[\mathrm{Fe/H}]\rangle = -2.8$ and the corrections required to deduce the primordial value.

Ryan et al, 2000 A=log(Li/H)+12



Fits all the Data

We Can Compare to CMB measures Of η when we Talk about the CMB