Forskningsanknytning
Part II
Strålningsprocesser VT09
Andreas Korn
D at high redshift

lots of absorption lines are seen blueward of Ly$\alpha$ in QSO spectra, they are due to absorption from the continuous QSO spectra in gas along the LOS (intergalactic clouds)
QSO studies

Inter-Galactic Medium

Milky Way

Quasar (QSO) at large redshift, $z > 2 - 3$

depending on the column (= total) density of element X along the line of sight (LOS), some or all of the light of the background QSO will be absorbed at X-specific wavelengths.
Rugers & Hogan (1996)

use Keck to measure D/H in Q0014+813 (two clouds at $z \approx 3.32$)

examine almost the whole Lyman series, but D is really only detected in the blue wing of Ly$\alpha$. This feature is believed not to be an H interloper (accidentally blue-shifted by 82 km/s) based on line-profile arguments.

Results:

$D/H = 1.9 \pm 0.4 \times 10^{-4}$

$\eta_{10} = n_b / n_{\gamma} \times 10^{10} = 1.7 \pm 0.2$

$\Omega_b = 0.012 \Omega_c$ (only $\approx 1\%$ of the critical density)
use Keck to measure D/H in Q1937–1009 (two clouds at $z \approx 3.57$)

examine a good part of the Lyman series, but D is only detected in the blue wing of Ly$\alpha$ and $\beta$. This feature is believed not to be an H interloper based on line-profile arguments. They also look at silicon and carbon lines.

Results:

$D/H = 2.3 \pm 0.3 \times 10^{-5}$

$\eta_{10} = n_b / n_\gamma \times 10^{10} = 6.6 \pm 4.0$

$\Omega_b = 0.046 \Omega_c$ (only $\approx 5\%$ of the critical density)
Both teams deem it sufficient to analyse a single system. If both measurements are real, then the interpretations are different due to different underlying paradigms:

Tytler et al.: take the lowest value you can find, as high values are likely caused by H interlopers

Rugers & Hogan: take the highest value you can find as lower values are likely affected by D processing (conversion to $^3$He)

This always assumes that “WYSIWYG” holds: no D is locked up in molecules or dust (probably ok in these metal-poor IGCs)
The Wilkinson Microwave Anisotropy Probe (Bennett et al. 2003, Spergel et al. 2007) measures the angular power spectrum of the CMB relevant for us: \( \omega_b = \Omega_b \, h^2 \) with \( h \) given by \( H_0 = 100 \, h \, \text{km Mpc}^{-1} \text{s}^{-1} \)

HST Key project: \( H_0 = 72 \pm 8 \, \text{km Mpc}^{-1} \text{s}^{-1} \) (Freedman et al. 2001)

http://space.mit.edu/home/tegmark/index.html
(CMB movies)
D in the post-WMAP era

\[ \eta_{10} = n_b / n_{\gamma} \times 10^{10} = 6.0965 \pm 0.2055 \]  
(Spergel et al. 2007)

\[ \omega_b = \Omega_b h^2 = 0.0223 \pm 0.0008 \]
\[ \Omega_b = 0.043 \Omega_c \]

\[ D/H = 2.58 \pm 0.14 \times 10^{-5} \]

Who was right then?
What do the observers say?

Kirkman, Tytler et al. (2003)

analyse D/H towards Q1243+3047; together with four other measurements this leads to a mean D/H of \(2.78 \pm 0.44 \times 10^{-5}\), in good agreement with WMAP.

The paradigm has thus changed towards assuming that the D/H differences are not real.

Note that the total LISM value is now believed to be \(2.31 \pm 0.24 \times 10^{-5}\) leaving less room for Galactic processing than previously assumed (Linsky et al. 2006).
The Solar spectrum

Li I 6707
How to observe lithium

Li I resonance doublet at 6707 Å

- get a decent spectrum
- determine the stellar parameters (using photometry/spectroscopy)
- derive log $\epsilon$ (Li)

main uncertainty: $T_{\text{eff}}$
(0.07 dex per 100 K)

primordial lithium

a way to potentially measure \( \log \varepsilon (\text{Li})_p \) was discovered in the early 1980s:

a certain subclass of ancient halo stars (unevolved, warm) was found to have a uniform lithium abundance

Spite & Spite 1982, Nature 297, 483

Fig. 5. \( N_{\text{Li}} \) versus \( \log T_{\text{eff}} \) for old halo stars

Keeping in mind the present uncertainties until the final discussion, we will admit that no depletion nor accretion of \(^7\text{Li}\) took place in the formation and evolution of the hottest halo dwarfs. Then, the lithium abundance defined by the “plateau” of the curve \( \log N_{\text{Li}} \) versus \( \log T_{\text{eff}} \), represents the lithium abundance which existed in the matter which formed the star, i.e. the abundance of lithium in the interstellar matter at the very beginning of the Galaxy \( 1.5 \times 10^9 \) yr ago. This abundance was \( \log N_{\text{Li}} = 2.05 \) or \( N_{\text{Li}} = 11.2 \times 10^{-11} N_H \).

In this first study, \( \eta_{10} \) could be constrained to

\[ \eta_{10} = 3 \pm 2 \]

giving clear evidence that the universe does not contain enough baryons to fall back on itself.
By studying stars in a narrow $T_{\text{eff}}$ range, Ryan et al. could show that there is a trend of $A(\text{Li})$ with $[\text{Fe/H}]$ of
\[ \frac{dA(\text{Li})}{d[\text{Fe/H}]} \approx 0.12 \]

This trend can be explained by Galactic production of lithium through cosmic-ray spallation processes in the ISM.

This trend has nonetheless been challenged recently by revised $T_{\text{eff}}$ calibrations.
Where do we stand?

\[ \log \varepsilon (\text{Li})_p = 2.63 \pm 0.03 \]

WMAP: Spergel et al. (2007)

\[ \log \varepsilon (\text{Li})_p = 2.09 \pm 0.19 \]

Ryan et al. (2000)

\[ \log \varepsilon (\text{Li})_p = 2.04 \pm 0.10 \]

Asplund et al. (2006)

Ways out?


\textbf{no detectable} real scatter around trend
potential biases for inferred Li\textsubscript{p}

- high resolution (spectral)
- high S/N ratios

atomic physics

- atomic data for lithium and iron

observations

- rotational mixing
- atomic diffusion and radiative levitation
- outliers (stars with peculiar Li abundances; What do they tell us? Simply disregard them?)

modelling

- extrapolation to A(Fe) = 0 (all stars have non-zero metallicity)
- non-LTE corrections

stellar physics

BBN

- $n_{\nu}$, $\tau_n$, $\sigma$

atomic physics

- high S/N ratios
- atomic data for lithium and iron

outliers (stars with peculiar Li abundances; What do they tell us? Simply disregard them?)
Uncertainties in BBN?

assumed $^7\text{Be} (d,p) \, 2 \, ^4\text{He}$ reaction rate too small?  

But:
Angulo et al. 2005
(ApJ 630, L105)
(X-section)$_{\exp}$ slightly smaller

no solution, but an aggravation of the problem
Atomic diffusion?

**pre-WMAP**
significant downturn of $A(\text{Li})$ with increasing $T_{\text{eff}}$ (Richard et al. 2002, ApJ 580, 1100)

**post-WMAP**
addition of turbulence (as needed in A stars) removes this problem with the predictions (Richard et al. 2005, ApJ 619, 538)

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**not observed!**

**depletion by 0.4 dex possible**

Age: $13.5 \pm 0.5$ Gyr
300 stars with $-5.00 < \log(Z) < -3.10$

Age: $13.5 \pm 0.3$ Gyr
How to observe atomic diffusion

compare abundances in TOP stars to those in stars at the base of the RGB, all drawn from a single population.

⇒ globular clusters are ideal objects for this purpose

\[ \Delta T_{\text{eff}} \approx 1000 \text{ K} \]
\[ \Delta \log g \approx 0.7 \text{ dex} \]

Gratton et al.: iron abundances agree!

How can one distinguish between atomic diffusion and modelling deficits?
A re-examination of atomic diffusion in NGC 6397

observations with VLT UT2 and FLAMES+UVES 3/2005 (SM) Korn, Gustafsson, Piskunov, Barklem & Grundahl):

• re-observe some of Gratton’s targets:
  5 bRGB and 5 TOP stars
• additionally, observe 2 SGB and 6 RGB stars
• exposure times up to 18 h!

standard abundances analysis using both photometric and spectroscopic stellar parameters
Abundance trends for metals

\[ \Delta \log \varepsilon = 0.21 \pm 0.07 \]

\[ \Delta \log \varepsilon = 0.07 \pm 0.07 \]

\[ \Delta \log \varepsilon = 0.06 \pm 0.07 \]

\[ \Delta \log \varepsilon = 0.16 \pm 0.05 \]
correcting for diffusion, the stellar lithium abundances can be reconciled with the CMB+BBN prediction (Korn et al. 2006, Nature 442, 657):

$$\log \varepsilon (\text{Li})_{\text{NGC 6397}} = 2.54 \pm 0.10$$

vs. $$\log \varepsilon (\text{Li})_p = 2.64 \pm 0.03$$  
(Spergel et al. 2007)

predicted by Michaud et al. (1984)

shown to be compatible with observations by Richard et al. (2005)
Summary

During these two lectures we looked at:

- **Deuterium in high-z QSO spectra** ($D_p$, absorption spectroscopy)
- **Helium in metal-poor H II regions** ($He_p$, emission-line studies)
- **Lithium in warm metal-poor halo stars** ($Li_p$, stellar spectroscopy)

A great variety of techniques describing the matter-light interaction in various astrophysical sources is used in these studies.
Outlook

From hindsight (post-WMAP), it has become clear that all inferred primordial abundances have been subject to (severe) systematic biases and uncertainties.

Using our refined knowledge of $A(X)_p$, we can now turn the problem around and improve our understanding of the physics of the sources (intergalactic clouds, H II regions, stars).

Nature supplies laboratories to study the universe, but it does not simply give away the answers.