High redshift deuterium abundance

Resolving the tension between quasar and CMB Ω_b measurements

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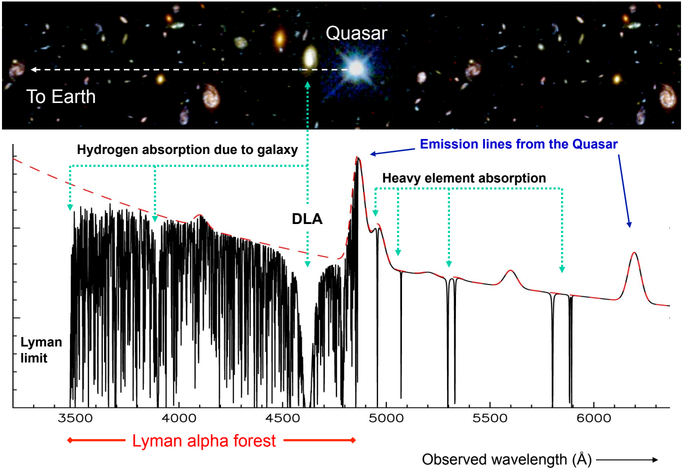
Outline

Outline

Motivation



Quasar
To Earth
Hydrogen absorption due to galaxy
Emission lines from the Quasar
Heavy element absorption
DLA
Lyman limit
3500
4000
4500
5000
5500
6000
Lyman alpha forest
Observed wavelength (Å)

Motivation

Table 4. The sample of D I/H I measurements considered robust in Pettini et al. (2008) together with updated estimates in the same absorbers and more recent, similarly precise measurements from other absorbers.

Reference	Absorption redshift	log(N(H I))	[X/H]	D I/H I [$\times 10^{-5}$]	$100\Omega_b h^2$
Burles & Tytler (1998a)	2.504	17.4 ± 0.07	-2.55 Si	4.00 ± 0.70	1.66 ± 0.18
Pettini & Bowen (2001)	2.076	20.4 ± 0.15	-2.23 Si	1.65 ± 0.35	2.82 ± 0.36
Kirkman et al. (2003)	2.426	19.7 ± 0.04	-2.79 O	2.43 ± 0.35	2.24 ± 0.20
Fumagalli et al. (2011)	3.411	18.0 ± 0.05	-4.20 Si	2.04 ± 0.61	2.49 ± 0.05
Noterdaeme et al. (2012)	2.621	20.5 ± 0.10	-1.99 O	2.80 ± 0.80	2.05 ± 0.35
Cooke et al. (2014), Pettini & Cooke (2012)	3.050	20.392 ± 0.003	-1.92 O	2.51 ± 0.05	2.19 ± 0.02
Cooke et al. (2014), O'Meara et al. (2001)	2.537	19.4 ± 0.01	-1.77 O	2.58 ± 0.15	2.16 ± 0.04
Cooke et al. (2014), Pettini et al. (2008)	2.618	20.3 ± 0.01	-2.40 O	2.53 ± 0.10	2.18 ± 0.03
Cooke et al. (2014)	3.067	20.5 ± 0.01	-2.33 O	2.58 ± 0.07	2.16 ± 0.03
Cooke et al. (2014), O'Meara et al. (2006)	2.702	20.7 ± 0.05	-1.55 O	2.40 ± 0.14	2.25 ± 0.03
Riemer-Sørensen et al. (2015)	3.255	18.1 ± 0.03	-1.87 O	2.45 ± 0.28	2.23 ± 0.16
Balashev et al. (2016)	2.437	19.98 ± 0.01	-2.04 O	1.97 ± 0.33	2.54 ± 0.26
This work	3.572	17.925 ± 0.006	-2.26 O	2.62 ± 0.05	2.14 ± 0.03
Weighted average[1]	—	—	—	2.55 ± 0.03	2.17 ± 0.03
Unweighted average[1]	—	—	—	2.53 ± 0.17	2.18 ± 0.08
Planck Collaboration et al. (2016)	—	—	—	2.45 ± 0.05	2.225 ± 0.016

The conversion between D I/H I and $\Omega_b h^2$ is based on nuclear rates from Coc et al. (2015) for standard Big Bang Nucleosynthesis. [1]Without the Balashev et al. (2016) and Noterdaeme et al. (2012) measurements

Figure: *Riemer-Sørensen et al. (MNRAS 468, 3239)*

D/H measurment

- Lyman Series:

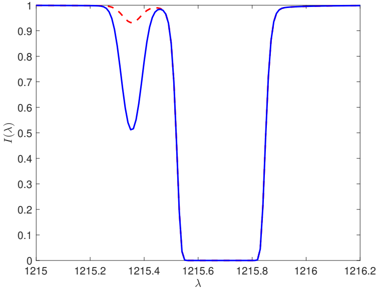
$$E_n = \frac{\mu e^4}{2(4\pi\epsilon_0\hbar)^2}\frac{1}{n^2} \quad \text{and} \quad \mu = \frac{Mm_e}{M+m_e}\,,$$

  where n is the principle quantum number, m_e and M are the mass of electron and nucleus.

  - Hydrogen and Deuterium: $\mu_H = \frac{1836}{1+1836}$ and $\mu_D = \frac{3670}{1+3670}$
  - Lyman α: $\lambda_H = 1215.67$ Å, $\lambda_D = 1215.34$ Å

D/H measurment

- Lyman α: $\lambda_H = 1215.67$ Å, $\lambda_D = 1215.34$ Å
- Left: $n_H = 10^{16}/cm^2$, $n_D/n_H = 10^{-3}$ (solid), 10^{-4} (dashed)
- Right: $n_H = 10^{16}$ (dotted), 10^{18} (dashed) and 10^{19} (solid) with $n_D/n_H = 10^{-4}$



Outline

Voigt Function

- Cross-section of a two-level system:

$$\sigma(\nu) = cf\sqrt{\frac{3\pi\sigma_T}{8}}\phi(\nu)\,,$$

where ν is the incoming photon energy, f is the oscillator strength, $\phi(\nu)$ is the Lorentzian

$$\phi(\nu) = \frac{\Gamma/4\pi^2}{(\nu-\nu_0)^2+(\Gamma/4\pi)^2}\,,$$

$E = h\nu_0$, and Γ is the spontaneous decay rate.

Voigt Function

- Doppler effect: $\nu_0 \to \nu_0 \left(1 + \frac{v_z}{c}\right)$
- Boltzmann distribution: $N(v_z) = \frac{exp(-v_z^2/(2kT/m))}{\sqrt{2\pi kT/m}}$

Voigt Function

- Intensity Profile: $I_\nu = I_0 e^{-N\alpha_\nu}$, and

$$\alpha_\nu = \frac{\sqrt{\pi}e^2}{m_e c}\frac{f}{\Delta\nu_D}H(a,u)\,,$$

where $\Delta\nu_D = \frac{b\nu_0}{c}$, $b = \sqrt{\frac{2kT}{m}}$, $u = \frac{(\nu-\nu_0)}{\Delta\nu_D}$ and $a = \frac{\Gamma}{4\pi\Delta\nu_D}$.

- Voigt Function:

$$H(a,u) = \frac{a}{\pi}\int_{-\infty}^{\infty}\frac{e^{-y^2}dy}{(u-y)^2+a^2}\,.$$

Voigt Function

- Absorption and Voigt Function:
  - Two-level system $\Rightarrow$ Lorentzian profile
  - Convolution of Boltzmann and Lorentzian

Outline

Kramers-Heisenberg Formula

- Kramers-Heisenberg formula

$$\frac{d\sigma}{d\Omega} = r_0^2 \left(\frac{\nu'}{\nu}\right) \left| \delta_{if} \vec{\epsilon}^{\alpha} \vec{\epsilon}^{\alpha'} + \frac{2\pi m_e \nu_{nf} \nu_{ni}}{\hbar} \right.$$

$$\left. \sum_n \left[\frac{(\vec{x} \cdot \vec{\epsilon}^{\alpha'})_{fn} (\vec{x} \cdot \vec{\epsilon}^{\alpha})_{ni}}{\nu_{ni} - \nu - i\Gamma_n/2} + \frac{(\vec{x} \cdot \vec{\epsilon}^{\alpha})_{fn} (\vec{x} \cdot \vec{\epsilon}^{\alpha'})_{ni}}{\nu_{ni} + \nu'} \right] \right|^2,$$

where $\nu(\epsilon^{\alpha})$ and $\nu'(\epsilon^{\alpha'})$ are the frequency (orientation) of the incoming and outgoing photon, and

$$\nu_{ab} = \frac{E_a - E_b}{h}\,.$$

Kramers-Heisenberg Formula

- Lyman α: $1s \to 2p \to 1s$

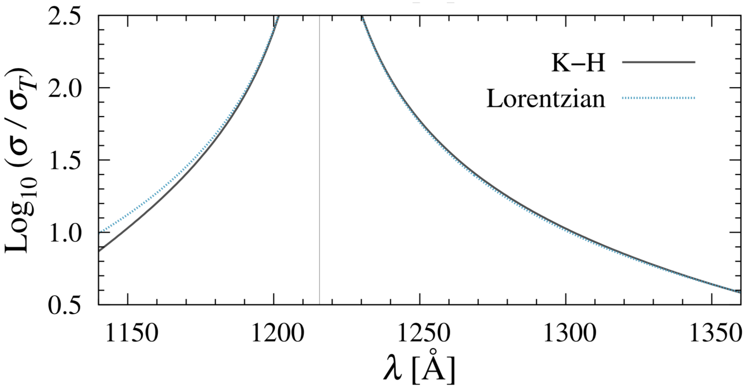


Figure: Kiehunn Bach, Hee-Won Lee, JKAS 47, no.5, 187(2014)

Kramers-Heisenberg Formula

- Kramers-Heisenberg formula

$$\frac{d\sigma}{d\Omega} = r_0^2\left(\frac{\nu'}{\nu}\right)\left|\delta_{if}\vec{\epsilon}^{\alpha}\vec{\epsilon}^{\alpha'} + \frac{2\pi m_e \nu_{nf}\nu_{ni}}{\hbar}\right.$$
$$\left.\sum_n\left[\frac{(\vec{x}\cdot\vec{\epsilon}^{\alpha'})_{fn}(\vec{x}\cdot\vec{\epsilon}^{\alpha})_{ni}}{\nu_{ni}-\nu-i\Gamma_n/2} + \frac{(\vec{x}\cdot\vec{\epsilon}^{\alpha})_{fn}(\vec{x}\cdot\vec{\epsilon}^{\alpha'})_{ni}}{\nu_{ni}+\nu'}\right]\right|^2.$$

- Rayleigh Scattering (Elastic): $1s \rightarrow np \rightarrow 1s$
- Raman Scattering (Inelastic): $1s \rightarrow np \rightarrow n's$ or $n'd$
- Example: $1s \rightarrow 4p \rightarrow$ Final states ($1s$, $2s$, $3s$ and $3d$)

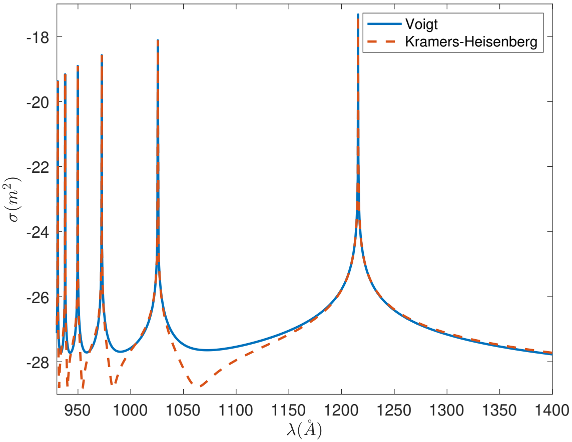
Kramers-Heisenberg Formula

- $\sigma(\nu) = \sigma^{Rayleigh}(\nu) + \sum_f \sigma_f^{Raman}(\nu)$.
- Doppler effect: $\nu_{ni} \rightarrow \nu_{ni}\left(1 + \frac{v_z}{c}\right)$.
- Boltzmann distribution: $N(v_z) = \frac{exp(-v_z^2/(2kT/m))}{\sqrt{2\pi kT/m}}$.

Outline

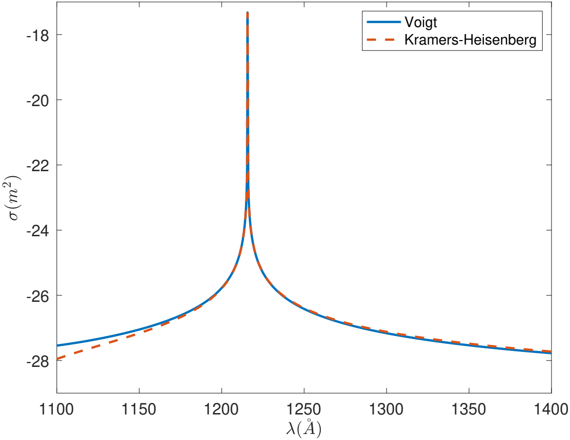
Cross Section

- Lyman Series:



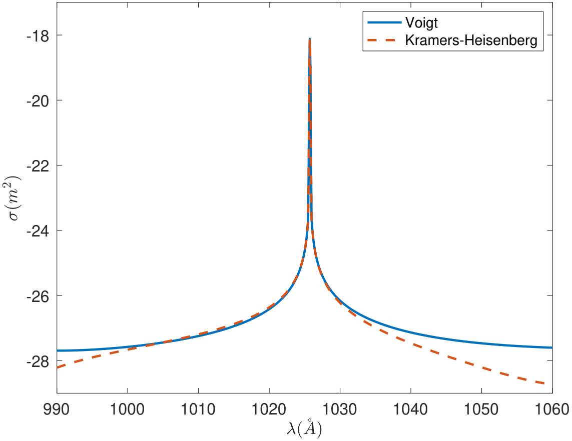
Cross Section

- Lyman α:



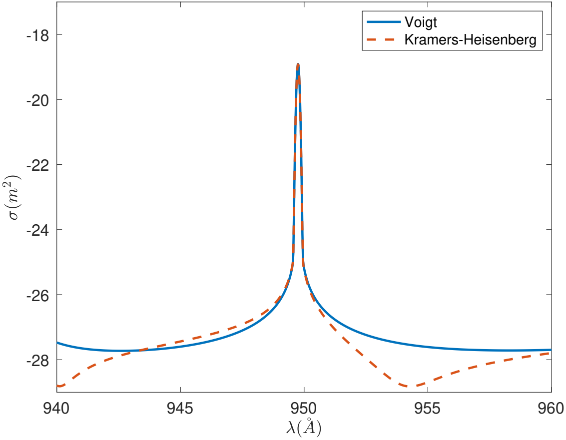
Cross Section

- Lyman β:



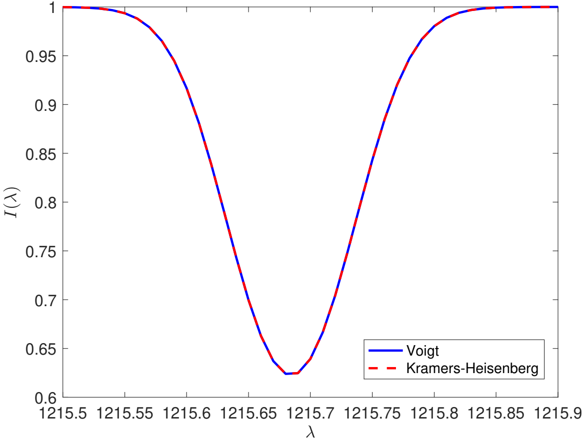
Cross Section

- Lyman γ:



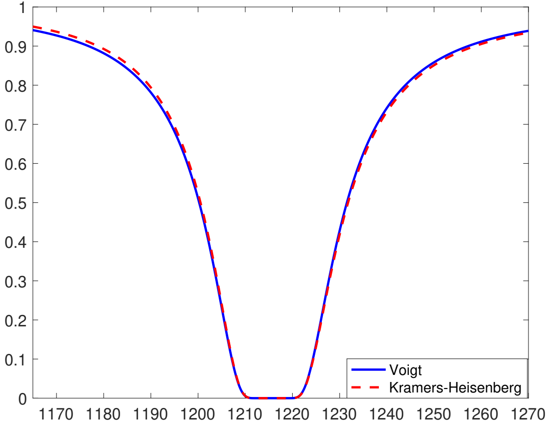
Intensity

- Lyman α with $\log N = 13.0$:



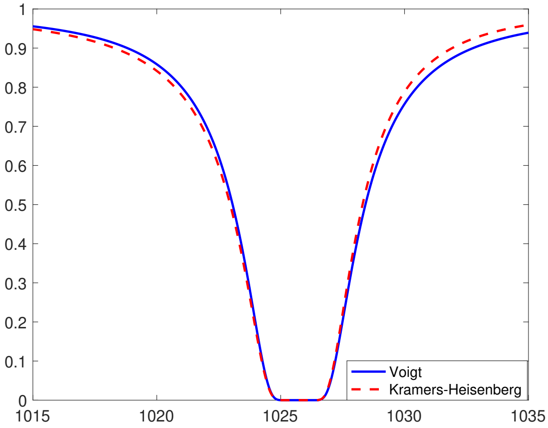
Intensity

- Lyman α with $\log N = 21.6$:



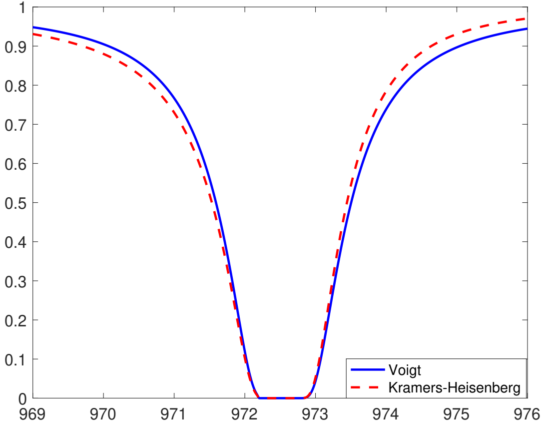
Intensity

- Lyman β with $\log N = 21.6$:



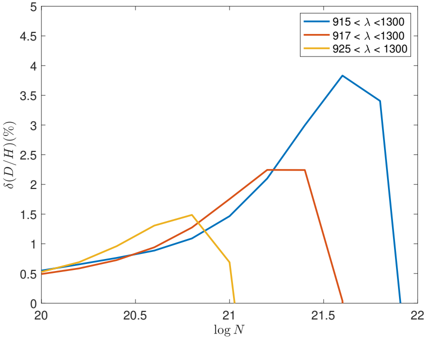
Intensity

- Lyman γ with $\log N = 21.6$:



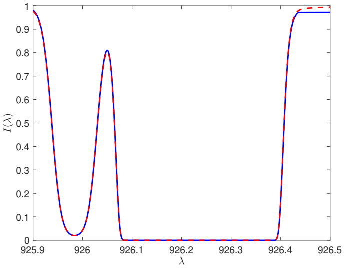
Fitting

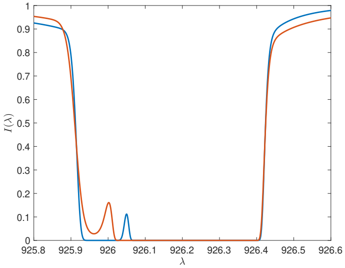
- $\delta(D/H) \equiv \frac{n_{voigt-fit}}{n_{fid}} - 1$
- Fitting Region:
  - blue: Lyα - Ly14
  - red: Lyα - Ly12
  - yellow: Lyα - Ly7



Fitting

- Fit the fiducial with Lyα - Ly7
  - Left: Lyman 7 ($n = 1 \to 8$) with $\log N = 20.6$
  - Right: Lyman 7 ($n = 1 \to 8$) with $\log N = 21.6$





Summary

- Deuterium Abundance
  - QSO: $D/H = (2.55 \pm 0.03) \times 10^{-5}$
  - CMB: $D/H = (2.45 \pm 0.05) \times 10^{-5}$
- Speed:
  - Voigt Profile: quick!!
  - Karmers-Heisenberg: slow!!