Quasar absorption lines

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A bit of history

• 1960: Matthews & Sandage: Discovery of radio source with point-source, blue optical counterpart (looks like a star)

→ quasi-stellar radio source → “quasar”
very peculiar star???

• 1963: Schmidt realises the emission lines of 3C273 are Balmer shifted by 16%
Same conclusion for 3C48 (z=0.37) by Greenstein & Matthews
A bit of history

- So quasars are very very bright objects at cosmological distances (For quasar **absorption lines**, it is almost all what we need to know)

- 1966: **Burbidge**: first detection of absorption lines in a quasar spectrum
The basics of quasar absorption lines

→ whiteboard
The basics of quasar absorption lines

The width depends on $b$ and depth on $N$, but the total surface of the line ($EW$) does not.

The shape depends on $b$ & $N$, as well as the $EW \rightarrow$ big mess.

The shape and $EW$ depend only on $N$. 
The Ly-alpha forest: gas in the IGM

The most numerous lines in quasar absorption spectra are Ly-alpha from the **InterGalactic Medium** → Ly-alpha forest

→ Gas everywhere?
The Ly-alpha forest: gas in the IGM

http://gigapan.com/gigapans/76215/
The Ly-alpha forest: gas in the IGM

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http://gigapan.com/gigapans/76215/
There are also galaxies

Sometimes, the quasar line of sight hits neutral gas → Damped Ly-alpha system (DLA)

DLAs are thought to arise within/next to galaxies (we'll talk about this later)
A quasar spectrum
Intervening systems: classify systems by $N(\text{HI})$

- $N(\text{HI}) \sim 10^{12} \text{ cm}^{-2}$ and over ten orders of magnitude
- A wide range of properties (very tenuous IGM to dense ISM)
- The same way over a wide redshift range
- Detection independent of the luminosity of the associated object

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**Lyα-forest**

**Ly-limit systems (LLS)**

**Damped Lyα systems (DLAs)**

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Prochaska et al. 2014

Kim et al. 2013

Rudie et al. 2013

Omeara et al. 2007

Noterdaeme et al. 2012c
e.g. Broad Absorption Lines
Gunn-Peterson effect: Neutral hydrogen regions overlap and cause complete ($\tau >> 1$) Ly-\(\alpha\) absorption blueward of the Ly-\(\alpha\) emission line.

No GP effect up to \(z=6\)  
→ The Universe is mostly ionised

GP trough appears at \(z \approx 6.3\) but varies strongly from one line of sight to the other  
→ The reionisation is patchy

Robertson et al. 2010

Becker et al. 2014
The very high-z: GRBs

- Gamma-ray bursts can be used as well

Lamb 2002

Chornock et al. 2014
What we observe is
\[ I = I_0 \exp(-\tau(\lambda)) \]

In principle, we know how to decompose each line into \( N, b, z \)

In practice: not easy to apply to Ly-alpha forest

What we want are the physical properties. \( \rightarrow \) Compare with models.
Physical conditions in the IGM

- Density

  \[ \log (\rho/\rho_c) \] vs. \[ \log N_{\text{HI}} \ (\text{cm}^{-2}) \]

  **Schaye 2000:** The observed column density is a fairly good tracer of the overdensities

- Temperature

  **Becker et al. 2011:** The smoothness of the lines is a fairly good indicator of the temperature
Physics \rightarrow we expect a relation between \textit{temperature} and \textit{density} \\
\rightarrow relation between \textit{width} and \textit{column density} of the Ly-alpha forest lines?

- The temperature – density relation
  \begin{align*}
  T = T_0 \gamma
  \end{align*}
  Competition between photoelectric heating and adiabatic cooling

Cooling is very slow, so IGM keeps trace of thermal history

\textit{Bolton et al. 2014}
Physical conditions in the IGM: evolution

- Reionisation

Production of ionising photons:

\[
\frac{dn_{\text{ion}}}{dt} = f_{\text{esc}} \zeta_Q \rho_{\text{SFR}}
\]

- fraction of ionising photons escaping a galaxy
- SFR density (M_{\odot}/yr/Mpc^3)
- H-ionising photon per unit SFR density

Recombination rate: depends on IGM temperature and density enhanced in overdensities
Physical conditions in the IGM: evolution

- Evolution (opacity/temperature)

Faucher-Giguère et al. 2008

High-resolution spectroscopy

Becker et al. 2013

Compositing of low-R spectra

HI ionisation by galaxies
Hell ionisation requires harder UV (300Å, quasars?), and the recombination rate is fast
Physical conditions in the IGM: evolution

- Evolution (opacity/temperature)

T increases with decreasing redshift because it then traces higher over-densities:
- bounded against cooling by expansion
- higher recombination rate so more atoms for photo-electric heating

Temperatures in over-densities

Boera et al. 2014
• Heavy elements are produced by stars in galaxies

- CIV always found for log NHI > 15
- CIV in ~50% at log NHI = 14.5
- Metallicity ~ 0.001-0.01 solar at z~2-3
- At z>>6, information on IGM will come mostly from metals

• How did they get into the IGM?
  → Constraints on outflow mechanisms and star-formation history
The Ly-alpha forest: tomography of the IGM

~Mpc resolution: We will need 1000 LoS/deg² (SDSS-III/BOSS: 17)
Quasar are not enough → use LBGs!

Steidel et al. 2009: S/N=30 per pixel @ R=5000 for r=24.5

Evans et al. 2012: S/N>8 per resolution element @ R=5000 for r=24.8

→ MOS@ELT

Lee et al. 2014: you don't need to resolve forest. S/N~4 @ R~1000 is enough to g~24

→ VLT is ~ok (?)
Shining of an IGM filament

- Filament in the cosmic web: Ly-alpha in emission

Cantalupo et al. 2014
Fig. 2. Fits to Ly\(\alpha\) (top), Ly\(\beta\) (middle), and Ly\(\gamma\) (bottom) \(\text{H}_1\) absorptions in the BG (left) and FG (right) spectra. Dashed purple, blue, and red lines mark the log \(N(\text{H}_1) > 18.0\) components in regions A, B, and C, while dash-dotted purple, blue, and red lines indicate the weaker components within the respective regions. Dash-dotted blue-gray lines signal low column density components between the three main regions that are also part of the absorption structure. Dotted gray lines in the BG-Ly\(\alpha\) panel indicate blended components from Si \(\text{ii} \lambda 1190\) and 1193 absorptions associated with \(z \approx 2.75\) DLA.

Finley et al. 2014
Gas in galaxies: Damped Lyman-alpha systems

At \( \log(NHI) > 20 \), all ionising photons are absorbed in the external layers

→ DLAs correspond to neutral gas
Huge increase of statistics mainly thanks to SDSS $\sim 100$ to several $10^4$

Petitjean et al. 1993

Noterdaeme et al. 2012c, 2014
How much gas in DLAs?

→ whiteboard
DLAs contain the bulk of neutral gas at high-$z$

They probe a wide range of redshift free from Malmquist bias.

- ground-based telescopes: $z>1.6$
- blending with Lyman-alpha forest becomes severe at $z>3.5$

Noterdaeme et al. 2009b
Cosmological density

- Systematics dominate
- $z > 3.5$ not well constrained: blending with Ly-alpha forest, need higher resolution (medium is ok)

Does the neutral gas behave like star-formation?

Hummmm....
- about 20 different elements detected in DLAs → smoking gun of star formation
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- Column density measurements are robust in DLAs: independent of physical parameters like temperature or density

- \( h\nu < 13.6 \text{ eV} \) → Metals mostly in a single ionisation stage (FeII, SiII, ZnII, OI, NI...)
  → \( N(\text{ZnII}) \sim N(\text{Zn}) \)
  → \( \text{ZnII/HI} = \text{Zn/H} \)
  → no ionisation correction

Abundances measurements in DLAs are accurate (typically 0.1 dex)
• **In practice: high vs low spectral resolution**

  - high R: Voigt-profile fitting
    - Apparent Optical Depth
  - low R: only Equivalent Widths
    → Assuming optically thin is very dangerous!

Metallicities have to be measured at “high” spectral resolution.
Zinc as proxy for iron? Barbuy et al. 2015 (Galactic buldge stars): \([\text{Zn/Fe}]\) decreases with increasing metallicity.

SN type II enrichment:
- overabundance of O compared to N
- overabundance of alpha elements compared to iron-peak

→ An example, \([\text{N/O}]\) vs \([\text{O/H}]\)
• **Depletion**

Does the gas-phase abundance represent the true abundance?

→ Several species tend to easily deplete onto dust grains (e.g. Fe, Ni, Cr), while other are more volatile (Zn, S)
• **Depletion**

Does the gas-phase abundance represent the overall abundance?

→ Several species tend to easily deplete onto dust grains (e.g. Fe, Ni, Cr), while other are more volatile (Zn, S)

→ $\frac{[\text{Zn}/\text{Fe}]}{[\text{Zn}/\text{H}]}$ increases with $[\text{Zn}/\text{H}]$

→ Higher detection rate of $\text{H}_2$ when both are high.

Noterdaeme et al. 2008a
Do we miss high-Z, high-NHI systems?

Boisse et al. 1998
Is there any direct evidence for dust in DLAs?

- Spectral index: MTM & Liske 04
- Photometric colours: Vladilo et al. 08
- Spectral stacking: Fukugita & Ménard 14 (z=2.2)
- Frank & Péroux 10
- Khare+ 12

$E(B-V)_{SMC}$ [mmag]

Slide from M. Murphy
CORALS (Ellison et al. 2005)

- 66 radio-selected QSOs
- Incidence of DLAs consistent with optically-selected quasars
- Total HI also consistent (within x2) with optical surveys

→ No bias...of what?

→ The bulk of neutral gas is not affected by dust-biasing
The age-metallicity relation: a long story

Lu et al. 1996

Galactic stars

DLAs

$q_0=0.1, H_0=50$
The age-metallicity relation: a long story

Lu et al. 1996

Kulkarni et al. 2002
The age-metallicity relation: a long story

Lu et al. 1996
Kulkarni et al. 2002
Prochaska et al. 2003
The age-metallicity relation: a long story

Wolfe et al. 2005, ARA&A: “This result is robust owing to the large value of \( \sum_i m_{Ni} \). This is important since the shape of \( f(N, X) \) indicates that \( <Z> \) is sensitive to the metallicity of systems with the largest values of \( N(H I) \). Because \( \sum_i m_{Ni} \geq 1 \times 10^{22} \text{ cm}^{-2} \) in each of the high-redshift bins, only unusual, very metal-rich systems with \( N(H I) > 10^{22} \text{ cm}^{-2} \) could increase \( <Z> \) significantly, i.e., only systems which depart significantly from the current \( N(H I) \) versus [M/H] relation could cause a marked increase in \( <Z> \).”

The age-metallicity relation: a long story

- Upper branch: follows the Metallicity-Luminosity but inconsistent with DLA metallicities
- Lower-branch: ok with DLA metallicities but out of Z-L relation.

Lu et al. 1996
Kulkarni et al. 2002
Prochaska et al. 2003
Ellison et al. 2005
The age-metallicity relation: a long story

- Lu et al. 1996
- Kulkarni et al. 2002
- Prochaska et al. 2003
- Ellison et al. 2005
- Rao et al. 2006
The age-metallicity relation: a long story

Lu et al. 1996
Kulkarni et al. 2002
Prochaska et al. 2003
Ellison et al. 2005
Rao et al. 2006
Rafelski et al. 2012
A fast change in metallicity at $z>4.7$?

Rafelski et al. 2014
Kulkarni and co-workers: sub-DLAs tend to be more metal-rich

→ does this mean more massive galaxies?
Kinematics

Basic principle

**Radial Infall**

\[ V_{\text{infall}} = 200 \text{ km/s} \]

**Rotating Disk**

\[ V_{\text{rot}} = 200 \text{ km/s} \]
Under pressure equilibrium: a simple two phase model

Are DLAs warm neutral medium or cold neutral medium?
Physical conditions in the neutral gas

Look for the difference between “Warm Neutral Medium” and “Cold Neutral Medium”

Idea: Temperature → Broadening of the lines

Doppler parameter: \( b^2 = 2k_B T/m + b_{\text{turb}}^2 \)

So, if we use two species (different masses), we may solve the degeneracy.

Problems: \( m \gg 1 \)  \( \Rightarrow \)  \( 2k_B T/m \)  negligible compared to \( b_{\text{turb}}^2 \)

HI (\( m=1 \)) but damped regime \( \Rightarrow \) no constraint on \( b \)

Solution: look for much less abundant “type” of hydrogen, so that the line is not saturated

![Graph showing the relationship between atomic mass and Doppler parameter.](image)

Noterdaeme et al. 2012b
**Physical conditions in the neutral gas**

**Idea:** \( \text{H}_2 \) forms better in cold dense environments

**Problem:** \( \text{H}_2 \) lines are weak and in the Lya-forest

**Solution:** high-resolution in the blue → **UVES @ VLT**

Possibility to detect one \( \text{H}_2 \) molecule for a million Hydrogen atoms → little \( \text{H}_2 \) in most DLAs ([Ledoux+03, Noterdaeme+08]) → mostly WNM
Physical conditions in the neutral gas

$H_2$ a nice probe of the local physical conditions

- Rotational levels of $H_2$: collisions, radiative excitations, shielding effects
- CI fine-structure levels: pressure, density

- $T \sim 100$K
- UV field
- $n \sim 1 - 100$ cm
- $D \sim$ pc
We can also use the radio domain: 21-cm

- emission (CNM+WNM): not possible yet at high-z
- absorption (CNM):

\[ N(\text{H}) = 1.835 \times 10^{18} \frac{T_e}{f_c} \int \tau(\nu) \, d\nu \]
Star-formation in the overall DLA population?

Star-formation

Fumagalli et al. 2015:
20 DLAs fields imaged with HST
no detection, even from stack

Very little in-situ star formation: is this surprising?

Rahmati & Schaye 2014
DLAs contain most of the neutral gas in the Universe

DLAs present significant amount of metal enrichment, increasing with time

DLAs contain generally little dust

DLAs are mostly WNM

Hot questions: Where is the CNM? Where is the star-formation (i.e. where are the supposed DLA galaxies)?
Idea 1: Look for metal-rich systems

More metals $\rightarrow$ More star-formation?

It works!

But we can be far from the galaxy:
- metals are spread far away, and
- probability of interception by quasar line of sight goes as $d^2$

Krogager et al. 2012, 2013
Idea 2: Look all around the quasar line of sight

→ Very time consuming
→ But when it works, you get very nice results!

Cool inflow onto massive galaxy

Bouché et al. 2013
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Hot questions: Where is the CNM? Where is the star-formation (i.e. where are the supposed DLA galaxies)?
Idea 3: Look for very high column densities

Statistically, using SDSS

In individual systems, using X-shooter

Notaerdaene et al. 2014

Notaerdaene et al. 2012a
Idea 3: Look for very high column densities

we can also use GRBs...

... but you have to be fast (RRM on VLT)
Idea 3: Look for very high column densities

...and we now also see systems beyond the “old” limit
...and guess what? They have $\text{H}_2$!
DLAs contain most of the neutral gas in the Universe

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Hot questions: Where is the CNM? Where is the star-formation (i.e. where are the supposed DLA galaxies)?
Idea 4: Look directly for the cold gas
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more lines-of-sight!

SDSS → VLT

need efficient selection
Idea 4: Look directly for the cold gas

More lines-of-sight!

SDSS → VLT

Need efficient selection

Tracers
Idea 4: Look directly for the cold gas
Idea 4: Look directly for the cold gas

We do detect cold gas, with new molecules!

1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd}, ... detections of CO in absorption all done at VLT
and CO is great because its excitation is dominated by CMB

\[
\frac{N_1}{N_0} = \frac{g_1}{g_0} e^{-E_{01}/kT_{01}}
\]

![Graph showing log(N(CO,J)/gj) vs E0j (K)]
Strongly supports the adiabatic cooling of the Universe ($\beta = -0.007 +/- 0.027$)
Fundamental physics

We can also constrain the variation of fundamental constants...

\[ \mu = \frac{m_p}{m_e} \]

\[ \lambda_i = \lambda_i^0 (1 + z_{abs}) (1 + K_i \frac{\Delta \mu}{\mu}) \]
We can also constrain the variation of fundamental constants...

\[ \mu = \frac{m_p}{m_e} \]

For (very) technical details, talk to Rahmani et al. 2013

\[ \lambda_i = \lambda_i^0 (1 + z_{abs}) \left(1 + K_i \frac{\Delta \mu}{\mu} \right) \]
$\Omega_b$

$D/H \sim 10^{-5}$

DI and HI very close in velocity space

Cooke et al. 2014
Quasar absorption lines can be used to probe gas with very different properties over very different scales as well as studying fundamental physics & cosmology.
# Many, many lines of sight

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<td>SDSS, DES</td>
<td>ZTF, DEcam, CFHT?</td>
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(non-ESO, non-OPTICON) Baryonic Acoustic Oscillations


This is large survey science