Quasars Probing Quasars

Jason X. Prochaska
UCO/Lick Observatory
(on behalf of J. Hennawi and G. Prochter)
Outline of Results

• Intro
  ✦ Traditional QAL studies
  ✦ QSO Pairs

• QSO-MgII Clustering
  ✦ $R_0 = 4.55 \pm 0.8 \text{ Mpc h}^{-1}$
    ‣ $M \sim 10^{12} \text{ Msol}$
  ✦ Proximity effect for optically thick systems

• MgII toward GRB vs QSO
  ✦ There are 4x more galaxies in front of GRB than QSOs!?

• QSO-LLS Clustering
  ✦ Strong signal at $z>2$
  ✦ Proximity effect

SDSS QSO $z=2.17$

High z QSO candidate
Where Credit is Due

Joe Hennawi
(UCB)
Ideas + Work

Gabe Prochter
(UCSC)
Work + Ideas

Me
Cheerleading
QAL Experiment

- Observe a quasar
  - Typically bright (V<19)
  - Generally z>2
- Study the gas between us and the QSO
  - Properties of the QSO are largely unimportant
  - Absorption-line spectroscopy

Keck Observatories
Quasar Continuum

The graph shows the relative flux of a quasar continuum as a function of wavelength (in Angstroms). Prominent features include a peak at Lyα at a wavelength of approximately 1215.67 Å, labeled as Lyα. Other absorption lines are marked as OVI and CIV. The redshift of the quasar, denoted as $z_q$, is given as 3.44.
• **Lyα forest**
  ✦ $N(\text{HI}) < 10^{17} \text{ cm}^{-2}$
  ✦ $\delta\rho/\rho < 10$
  ✦ Lots o’ science

• **Lyman Limit Sys**
  ✦ $N(\text{HI}) > 10^{17} \text{ cm}^{-2}$
  ✦ $\delta\rho/\rho \sim 100$
  ✦ Unexplored

• **Damped Lyα Sys**
  ✦ $N(\text{HI}) > 2 \times 10^{20} \text{ cm}^{-2}$
  ✦ Galaxies

• **Metal-line Sys**
  ✦ MgII
  ✦ CIV
  ✦ ETC.
Frequency distribution

$\alpha = -1.8$

Single Power–Law

Gamma Function

Double Power–Law
• >120 DLA
  ✦ Evolution in both unweighted and <Z>
  ✦ -0.26 dex per Δz
  ✦ About 2x per Gyr

• Scatter
  ✦ Roughly constant with z
  ✦ Uniform population?

• Metallicity floor
  ✦ [M/H] > -2.6
  ✦ DLA are linked to current or recent SF

(95% c.l.)
Chemical Abundances

- **Dust-to-gas ratio**
  - Zn/Fe, Si/Fe
  - Depletion patterns
  - Obscuration implications
- **Molecular content**
- **Star-formation histories**
  - Si/Fe, N/O, z
  - ‘Morphology’
    - Dwarf galaxies
    - Outer spiral galaxy

Vladilo (2004)
Chemical Abundances

- Dust-to-gas ratio
  - Zn/Fe, Si/Fe
  - Depletion patterns
  - Obscuration implications
- Star-formation histories
  - Si/Fe, N/O, Z
  - ‘Morphology’
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Dessauges-Zavadsky et al. (2004)
What we (think we) know:

- $N_{\text{HI}}$
- Metallicity
- Dust-to-gas ratio
- Velocity field
- 1D Power spectrum
- Chemical abundances

What we don’t know:

- Density
- Size
- Mass of the host galaxy
- Properties of the QSO host
- Temperature
- Stars associated with the gas
Quasar Pairs

Neutral Gas

Ionized Gas

Foreground QSO

Background QSO
**Quasar Pairs: Previous work**

- **Low redshift**
  - Projected pairs
  - Coherence of Ly\(\alpha\) lines
    - \(\sim\) Mpc scales
    - Suggest these ‘clouds’ fill large volume

- **High redshift**
  - Gravitational lenses
    - Small separation
    - Impressive coherence
  - Small sample

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Dinshaw et al.
**Quasar Pairs: Previous work**

- **Low redshift**
  - **Projected pairs**
  - **Coherence of Ly$\alpha$ lines**
    - Mpc scales
    - Suggest these ‘clouds’ fill large volume

- **High redshift**
  - **Mainly gravitational lenses**
  - Small separation
  - Impressive coherence
  - Small sample of projected pairs
  - Mainly $>1'$ separation

1997MNRAS.285..209C
SDSS Survey

- **Data Release 4**
  - Over 3000 deg$^2$
  - Over 40,000 quasars

- **Spectral quality**
  - $R = 2000$
  - $\lambda = 3800 - 9200$ Ang

- **Fiber survey**
  - Collisions limit placement to 1’
    - 1’ = 1.5 Mpc h$^{-1}$ at z=2
**Close QSO Pairs**

- **SDSS Photometry**
  - Candidate QSOs near known SDSS QSOs
  - Follow-up spectra at APO
    - J. Hennawi thesis

- **Terrific success**
  - Current sample
    - >50 sub-arcminute pairs
  - Additional follow-up spectra
    - Lyα forest properties
    - QAL clustering
    - Etc.

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High z QSO candidate

SDSS QSO $z=2.17$

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Graph showing spectral data with wavelength ($\lambda$) on the x-axis and intensity ($I$) on the y-axis.
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  - Traditional QAL studies
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  - $R_0 = 4.55 \pm 0.8$ Mpc $h^{-1}$
  - $M \sim 10^{12}$ Msol
  - Proximity effect for optically thick systems

- **MgII toward GRB vs QSO**
  - There are 4x more galaxies in front of GRB than QSOs!?

- **QSO-LLS Clustering**
  - Strong signal at $z>2$
  - Proximity effect

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Prochter, Hennawi, Prochaska (2006)
MgII Search in QSO Spectra

SDSS Spectra
\[ \frac{dN}{dz} \text{ of MgII} \]

- **\( \frac{dN}{dz} \)**
  - Number of absorbers per unit redshift
  - Roughly, 1 QSO has 1 unit of redshift coverage

- **SDSS**
  - 20,000 quasars with sufficient SNR
    - Automatically identify 10,000 MgII systems
    - Each is verified by eye
  - Stat sample is 7000 with Rest EW > 1 Å
\[ \frac{dN}{dX} \text{ of MgII} \]

- \( \frac{dN}{dX} \)
  - **Number of absorbers per unit cosmological distance**
  - Assume LCDM
  - Proportional to the number density times cross-section
  - \( \frac{dN}{dX} \propto n \sigma \)

**Result**
- **Minimal evolution at \( z > 1 \)**
  - Suggests the number density is not significantly evolving
  - \( M < 10^{12} \text{ Msol} \)
  - Press-Schechter argument

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Prochter, Prochaska, & Burles (2006)
MgII-QSO Pairs (Transverse)

Contours of foreground QSOs

Observed MgII at $z_{\text{qso}}$

Contours of foreground QSOs

$R$ (Mpc h$^{-1}$)
**Correlation func.**
- $\xi_T = (R/R_0)^\gamma$
- Assume $\gamma = -1.6$

**Results**
- $R_0 = 4.55 \pm 0.8 \text{ Mpc h}^{-1}$
  - QSO-QSO: $R_0 = 5 \text{ Mpc h}^{-1}$
  - LBG-LBG: $R_0 = 3 \text{ Mpc h}^{-1}$
- No significant redshift evolution
\[ \xi_T = b_{\text{Mg}} \, b_{\text{qso}} \, \xi_{\text{DM}} \]

Mo & White formalism
MgII-QSO Clustering (EW)

- **Cut on MgII EW**
  - *Equivalent Width*
    - Driven by velocity field of MgII gas
  - Examine mass dependence
- **Results**
  - No systematic difference
  - Contradicts results from LRG (Bouche)?
Photoevaporation of clouds (Bertoldi 1989)
**MgII-QSO Clustering (Radial)**

- **Radial clustering**
  - Complicated by QSO redshift error
  - Corrected to MgII emission
  - 300 km/s uncertainty

- **Results**
  - z<1.4
    - Stronger signal in fainter QSOs
    - Clear proximity effect
  - z>1.4
    - Absence of signal indicates proximity effect

![Graph showing radial clustering](image_url)
MgII-QSO Summary

• SDSS Sample
  ✦ Supplemented by 2QZ
  ✦ Automated MgII search

• Transverse Clustering
  ✦ $R_0 = 4.55 \pm 0.8$ Mpc h$^{-1}$
    ✦ No redshift dependence
    ✦ No EW dependence
  ✦ Suggests mass of $\sim 10^{12}$ Msol
    ✦ Crude estimate, but one of the best now available

• Line-of-sight clustering
  ✦ Minimal enhancement
    ✦ Less enhancement for brighter QSOs
  ✦ Proximity effect for optically thick absorbers
    ✦ Enhancement of CIV, NV?
Introduction

Traditional QAL studies

QSO Pairs

QSO-MgII Clustering

$R_0 = 4.55 \pm 0.8 \text{ Mpc h}^{-1}$

$M \sim 10^{12} \text{ Msol}$

Proximity effect for optically thick systems

MgII toward GRB vs QSO

There are 4x more galaxies in front of GRB than QSOs!

QSO-LLS Clustering

Strong signal at $z > 2$

Proximity effect

Prochter et al. (2006)
MgII: GRB vs QSO

ON THE INCIDENCE OF STRONG Mg II ABSORBERS ALONG GRB SIGHTLINES

G.E. Prochter¹, J.X. Prochaska¹, H.-W. Chen², J. S. Bloom³, M. Desaules-Zavadsky⁴, R. J. Foley⁵, M. Pettini⁵, A. K. Dupree⁶, P. Guhathakurta¹

Submitted to ApJL

ABSTRACT

We report on a survey for strong (rest equivalent width \( W_r \geq 1 \text{Å} \)), intervening Mg II systems along the sightlines to long-duration gamma-ray bursts (GRBs). The GRB spectra which comprise the survey have a heterogeneous mix of resolution and wavelength coverage, but we implement a strict, uniform set of search criteria to derive a well-defined statistical sample. We identify 15 strong Mg II absorbers along 12 GRB sightlines (nearly every sightline exhibits at least one absorber) with spectra covering a total pathlength \( \Delta z = 13.8 \) at a mean redshift \( \bar{z} = 1.1 \). In contrast, the predicted incidence of such absorber systems along the same path length to quasar sightlines is only 3.4. The roughly four times higher incidence along GRB sightlines is inconsistent with a statistical fluctuation at greater than 99.9% c.l. Several effects could explain the result: (i) dust within the Mg II absorbers obscures faint quasars giving a lower observed incidence along quasar sightlines; (ii) the gas is intrinsic to the GRB event; (iii) the GRB are gravitationally lensed by these absorbers. We present strong arguments against the first two effects and also consider lensing to be an unlikely explanation. The results suggest that at least one of our fundamental beliefs on absorption line research is flawed.

Subject headings: gamma rays: bursts
MgII Result for non-QAL Folks

Q Q Q Q Q

G G G G G

L* galaxy with MgII gas

Earth

Earth
MgII Search in QSO Spectra

Normalized Flux

Wavelength (Ang)

SDSS Spectra
• $dN/dz$
  ✦ Number of absorbers per unit redshift
  ✦ Roughly, 1 QSO has 1 unit of redshift coverage

• SDSS
  ✦ 20,000 quasars with sufficient SNR
  ▶ Automatically identify 10,000 MgII systems
  ▶ Stat sample is 7000 with Rest EW > 1Å

Prochter, Hennawi, Prochaska (submitted)
GRB MgII

- MgII
  - Often establishes the GRB redshift (z<2.5)
  - Rest EW > 2Å in most cases

- Intervening MgII
  - Easy to identify
  - Even with low-res data
  - Limited to large EW systems in many cases

- GRB 970508
  - Even an example in the first optical spectrum
GRAAASP Swift Sample

Relative Flux vs. Relative Velocity (km/s)

- GRB050730 z=1.773
- GRB050820 z=1.430
- GRB051111 z=1.189
- GRB060418 z=0.656

MgII 2796
MgII 2803

MgII 2796
MgII 2803

MgII 2796
MgII 2803

MgII 2796
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MgII 2796
MgII 2803
Table 1. Survey Data for Mg II Absorbers Along GRB Sightlines

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<tr>
<th>GRB</th>
<th>z_{GRB}</th>
<th>z_{start}</th>
<th>z_{end}</th>
<th>z_{abs}</th>
<th>W_r(2796 Å)</th>
<th>Δv (km s^{-1})</th>
<th>Reference</th>
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<td>0.656</td>
<td>1.036 ± 0.012</td>
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</table>

W_r(2796) ≥ 1 Å Mg II Statistical Sample
Statistically Solid Result

GRB MgII systems
QSO–Predicted MgII systems
Possible Explanations

• Dust obscuration?
  ✦ MgII absorbers contain dust
    ‣ Could remove quasars from a magnitude limited sample
    ‣ Underestimate $dN/dz$
  ✦ But, dust content is low
    ‣ Effect is small

• Gas is Intrinsic to the GRB?
  ✦ $v > 100,000$ km/s!
  ✦ Galaxies have been identified

• Gravitational lensing?
  ✦ One MgII per sightline
    ‣ Double lens enhancement
  ✦ But, flux counts are flat
    ‣ No GRB pairs?

• Beam size? (Frank et al.)
  ✦ Very unlikely
Bizzare (fundamental?) result
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---

Hennawi & Prochaska (2006)
QSO-LLS Pairs

- **SDSS Quasars**
  - Standard identification
  - FWHM=2Å spectra

- **QSO Pairs**
  - SDSS photometry
  - APO follow-up
  - 2DF QSO’s too

- **Follow-up spectra**
  - Keck, Gemini
  - FWHM ~ 2Å resolution
  - SNR > 5 per pixel

- **Identify HI absorbers**
  - $N_{\text{HI}} > 10^{17}$ cm$^{-2}$

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Hennawi et al. (2006)
Sample Spectra

$z_{bg} = 2.60 \quad R = 794 \text{ kpc/h}$

$z_{bg} = 2.38 \quad R = 315 \text{ kpc/h}$

$z_l = 1.82 \quad J0127+1507$

Hennawi et al. (2006)
### $N_{\text{HI}} > 10^{19}$ Sample

#### Table 1
Super-LLSs Near Quasars from QPQ1

| Name                  | $z_{bg}$ | $z_{fg}$ | $\Delta \theta$ | $R$ (h$^{-1}$ kpc) | $z_{abs}$ | $|\Delta v|$ (km s$^{-1}$) | $\Delta v_{fg}$ (km s$^{-1}$) | log $N_{\text{HI}}$ (cm$^{-2}$) | $g_{UV}$ | Telescope |
|-----------------------|----------|----------|-----------------|---------------------|-----------|------------------------|-----------------------------|--------------------------------|---------|------------|
| SDSSJ0225−0739        | 2.99     | 2.440    | 214.0           | 4310                | 2.4476    | 690                    | 500                         | 19.55 ± 0.2                   | 5       | SDSS       |
| SDSSJ0239−0106        | 3.14     | 2.308    | 3.7             | 72                  | 2.3025    | 540                    | 1500                        | 20.45 ± 0.2                   | 6369    | Keck       |
| SDSSJ0256+0039        | 3.55     | 3.387    | 179.0           | 4195                | 3.387     | 20                     | 1000                        | 19.25 ± 0.2                   | 20      | SDSS       |
| SDSSJ0338−0005        | 3.05     | 2.239    | 73.5            | 1415                | 2.2920    | 960                    | 1500                        | 20.9 ± 0.2                    | 13      | SDSS       |
| SDSSJ0800+3542        | 2.07     | 1.983    | 23.1            | 415                 | 1.9828    | 30                     | 1500                        | 19.0 ± 0.15                   | 488     | Keck       |
| SDSSJ0833+0813        | 3.33     | 2.516    | 103.4           | 2112                | 2.505     | 980                    | 1000                        | 19.45 ± 0.3                   | 18      | SDSS       |
| SDSSJ0852+2637        | 3.32     | 3.203    | 170.9           | 3917                | 3.211     | 550                    | 1500                        | 19.25 ± 0.4                   | 13      | SDSS       |
| SDSSJ1134+3409        | 3.14     | 2.291    | 209.2           | 4073                | 2.2879    | 320                    | 500                         | 19.5 ± 0.3                    | 11      | SDSS       |
| SDSSJ1152+4517        | 2.38     | 2.312    | 113.4           | 2216                | 2.3158    | 370                    | 500                         | 19.1 ± 0.3                    | 30      | SDSS       |
| SDSSJ1204+0221        | 2.53     | 2.436    | 13.3            | 267                 | 2.4400    | 370                    | 1500                        | 19.7 ± 0.15                   | 625     | Gemini     |
| SDSSJ1213+1207        | 3.48     | 3.411    | 137.8           | 3246                | 3.4108    | 30                     | 1500                        | 19.25 ± 0.3                   | 39      | SDSS       |
| SDSSJ1306+6158        | 2.17     | 2.111    | 16.3            | 302                 | 2.1084    | 200                    | 300                         | 20.3 ± 0.15                   | 420     | Keck       |
| SDSSJ1312+0002        | 2.84     | 2.671    | 148.5           | 3129                | 2.6688    | 200                    | 500                         | 20.3 ± 0.3                    | 23      | SDSS       |
| SDSSJ1426+5002        | 2.32     | 2.239    | 235.6           | 4529                | 2.2247    | 1330                   | 500                         | 20.0 ± 0.15                   | 19      | SDSS       |
| SDSSJ1430−0120        | 3.25     | 3.102    | 200.0           | 4517                | 3.115     | 960                    | 1500                        | 20.5 ± 0.2                    | 26      | SDSS       |
| SDSSJ1545+5112        | 2.45     | 2.240    | 97.6            | 1873                | 2.243     | 320                    | 500                         | 19.45 ± 0.3                   | 30      | SDSS       |
| SDSSJ1635+3013        | 2.94     | 2.493    | 91.4            | 1861                | 2.5025    | 820                    | 500                         | > 19                          | 111     | SDSS       |

**Note.** — Optically thick absorption line systems near foreground quasars. The background and foreground quasar redshifts are denoted by $z_{bg}$ and $z_{fg}$, respectively. The angular separation of the quasar pair sightlines is denoted by $\Delta \theta$, which corresponds to a transverse comoving separation of $R$ at the foreground quasar redshift. Absorber redshift is indicated by $z_{abs}$, and $|\Delta v|$ is the velocity difference between the absorber redshift and our best estimate of the redshift of the foreground quasar. Our estimated error on the foreground quasar redshift is denoted by $\Delta z_{fg}$. Foreground quasar redshifts and redshift errors were estimated according to the detailed procedure described in § 4 of QPQ1. The logarithm of the column density of the absorber from a fit to the H I profile is denoted by log $N_{\text{HI}}$. The column labeled “Telescope” indicates the instrument used to observe the background quasar. The quantity $g_{UV} = 1 + F_{\text{QSO}}/F_{\text{UVB}}$ is the maximum enhancement of the quasars ionizing photon flux over that of the extragalactic ionizing background at the location of the background quasar sightline, assuming that the quasar emission is isotropic (see Appendix A of QPQ1). We compare to the UV background computed by F. Haardt & F. Madau (2006, in preparation)

Hennawi & Prochaska (2006)
Absorbers

- $N_{HI} > 10^{19}$ cm$^{-2}$
- Malmquist bias may be important
- Line blending
- Control by removing systems with $N_{HI} \sim 10^{19}$ cm$^{-2}$

Quasars

- SDSS
- 2QZ
- APO sample

Hennawi & Prochaska (2006)
Correlation func.

\[ \chi = \left( \frac{R}{R_0} \right)^\gamma \]

Assume

- \( \gamma = -1.6 \) (Blue)
- \( \gamma = -2 \) (Red)

Results

- \( R_0 = 9.2 \pm 1.5 \text{ Mpc h}^{-1} \)
- LBG-LBG: Green
- \( R_0 = 5 \) for \( \gamma = -2 \)
- In the transverse direction from quasars, the presence of strong Lya is enhanced

Hennawi & Prochaska (2006)
Clustering Anisotropy

• **Line-of-sight**
  ✦ Probability of intersecting an absorber
  ‣ Dependent on size
  ‣ Project clustering func.
  ✦ Compare with observed rate

• **Results**
  ✦ Proximate DLAs
    ‣ 2x enhancement
    ‣ RusseI et al. (2006)
  ✦ Our prediction
    ‣ >5x enhancement
    ‣ At least 50% are 'missing'
  ✦ Proximity effect for DLA!
    ‣ Implies typical volume density of \( n_{\text{HI}} = 10^{-1} \text{ cm}^{-3} \)

![Graph showing clustering anisotropy](Hennawi & Prochaska (2006))
Hennawi & Prochaska (2006)
- **QSO ionizes outer skin**
  - Gas recombines
  - 60% of the QSO radiation is emitted in Lya
    - Relatively high surface brightness
- **Investigate**
  - QSO emission
    - Anisotropy
    - Lifetime
  - Absorber size
    - Size/Geometry
    - Volume density

Adelberger et al. (2006)
$g_{UV} = 7900 \times UVB$

- Expect $\mu_{Ly\alpha} = 19.5 / sq''$

**Observe**
- Gemini (3hr integration)
- No unresolved emission
  - QSO anistropy?
  - But, note the intriguing feature in the 1D spectrum

**Future**
- Sample of over 10 fluorescence candidates
- Stay tuned...

Hennawi & Prochaska (in prep)
QSO Halo Gas

1204+0221

RA=12:04:16.69 DEC=+02:21:11.0

$\Delta \theta=13.3 \quad \alpha_{\text{pos}}=-61.8 \quad \Delta_{RA}=-86.0 \quad \Delta_{DEC}=-22.8$

$z=2.53 \quad i_q=19.01 \quad i_p=20.53$
**QSO Halo Gas**

- **Metallicity**
  - High: $[\text{Si/H}] > -0.5$

- **Velocity field**
  - Extreme
  - Suggestive of outflow
  - ‘Wind’ of 100’s km/s

- **Ionization state**
  - Modest: Low SiIV/SiII
  - But, high NII/NI
  - Consistent with low UV flux but high X-Ray

![Normalized Flux vs Relative Velocity (km/s)](chart)

**Lines:**
- SiIV 1393
- SiII 1526
QSO-LLS Clustering

**Anisotropic clustering**
- **Transverse**
  - \( R_0 = 9.2 \pm 1.5 \text{ Mpc h}^{-1} \)
- **Proximate prediction**
  - Expect one LLS per QSO
  - Observe \( \sim 2x \) increase in DLA
- **Implication:** QSO ionization of \( N_{\text{HI}} > 10^{19} \) absorbers
  - \( n_{\text{HI}} \sim 10^{-1} \text{ cm}^{-3} \)

**Other applications**
- **Fluorescence**
  - QSO ‘beaming’, lifetime
  - Size, geometry
- **High resolution studies**
  - Gas kinematics, ionization, metallicity in QSO Halos