Revealing the Origins and Environments of Mg II Absorbers with the SDSS and 3D-HST

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Outline

• Background & Motivation
• Statistical analyses using new large samples of Mg II
  • Stacking & Galaxy-Absorber Correlations in the SDSS
• Direct detections of Mg II host galaxies at high-z
  • New results from the 3D-HST Survey (Lundgren et al. 2012)
• Future Work
Collaborators

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  + the greater SDSS I/II & III, 3D-HST and AUS Collaborations
What are Quasar Absorption Lines?

- Absorption features in the spectra of quasars, produced by gas and dust
- Probes of:
  - Quasar outflows & host galaxies
  - Foreground galaxies: gas halos, disks, star-forming regions
  - Intergalactic medium
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"Ly-α Forest": Foreground Neutral Hydrogen
Metals
Quasar Spectra: Cosmic Core Samples

Just as ice cores from the Arctic provide a chemical history of the Earth...

The spectrum of a distant quasar can trace the evolution of the baryon content of the Universe throughout as much as 90% of cosmic history.
Quasar Spectra: Cosmic Core Samples

Animation Credit: Andrew Pontzen, Cambridge
QUASAR SPECTRA: COSMIC CORE SAMPLES
QALs as probes of galaxies and their environments

- Quasar Absorption Lines (QALs) trace gas, not stars!
  - The detection of luminous matter becomes more difficult at high-z... but not so for QALs
  - QALs are sensitive to wide ranges in metallicity, $N_{\text{HI}}$, kinematics, & ionization temperatures
- QALs provide direct, luminosity independent measurements of:
  - The gas content of galaxies ($\leq 200$ kpc)
  - Galaxy environments (e.g., low luminosity satellites, tidal streams)
  - Halo-disk processes (e.g., gaseous disks, outflows, cold gas accretion)
  - IGM
Persistent Challenges

- In theory, QALs are exceptional probes of galaxies. However,
  - QAL hosts are often too faint for imaging confirmation
  - It is often unclear which part of the galactic structure is being probed

SOAR 4.1m imaging (Meiring et al. 2011) and SDSS DR7 Spectrum of Q1436-0051

z=0.738
z=0.928
**Persistent Challenges**

- No obvious trends among local ($z < 0.4$) absorbing galaxies

Chen et al. 2010
Persistent Challenges

Redshift

Z = 0.84

Z = 2.14

Z = 2.12

Z = 1.97

Z = 2.01

Z_{QSO} = 2.134

Intervening

Associated / Intrinsic

v/c

0.2

0.05

0
Motivation for studying QAL origins & Environments

• Outstanding questions regarding the origins and environments of QALs:
  • How does one best distinguish quasar outflows from foreground matter in the Hubble flow?
  • What types of galaxies host what types of QALs?
  • How are QALs generally distributed in galactic haloes, and what processes do they primarily probe?

• With these determined, we can use QALs to expand our understanding of gas accretion and feedback processes in galaxies and the evolution of the content & distribution of baryonic matter from high-z
**Mg II Absorbers**

- Easily identifiable doublet (2796, 2803Å)
- Arises in photo-ionized gas with T~10,000K
  (Bergeron & Stasinska 1986; Hamann 1997)
- Prolific in optical spectra for 0.3≤z≤2.0
- Some association with DLAs (N_{HI}>10^{19} \text{ cm}^{-2})
  (Wolfe et al. 1986; Turnshek et al. 1986)
- Associated with luminous galaxies, 0.5-0.7 L*
Mg II Origins

- Classical Picture:
  - kinematic structure in strong lines (e.g., Churchill & Vogt 2001)
  - absorption equivalent width $\propto$ velocity dispersion of galaxy halo (e.g., Bahcall & Spitzer 1969)

- But new insights from the SDSS have tested (and challenged) this paradigm....
The Sloan Digital Sky Survey

- Dedicated 2.5m telescope at Apache Point Observatory, NM
- 120 megapixel camera with ugriz filter set
- Multi-object spectrograph (640 fibers)
- Seventh Data Release (DR7)
  - ~10,000 sq. degrees imaged
  - ~1 million galaxy spectra
  - ~110,000 quasar spectra
SDSS DR7 QAL PIPELINE

105,783 Quasars
DR7 Quasar Catalog
(Schneider et al. 2007)

Spectrum

Continuum Fitting

Line Detection

Redshift ID

Confidence Grading

QAL Catalog (York, Lundgren, et al. 2012 in prep.)
- ~60,000 QALS of various species
- 0.3 < z < 4.6
Ions identified by
the SDSS DR7
absorber pipeline
(York et al. 2006)
Example Output

\[ z_{\text{QSO}} = 3.0385 \quad m_i = 17.932 \]
SDSS J145907.19+002401.2

$z_{\text{QSO}} = 3.0385 \quad m_i = 17.932$

$z = 1.39448 \quad A \quad z = 2.29242 \quad A \quad z = 2.76708 \quad A \quad z = 2.89421 \quad C$
SDSS-III Baryon Oscillation Spectroscopic Survey

- 5-year survey in the SDSS-I/II footprint (10,000 deg\(^2\))
  - 1.5M LRGs to z~1
  - ~200,000 quasars (most at 2<z<4)
- Upgrades to the SDSS spectrograph
  - moderately higher throughput, resolution
  - broader wavelength coverage
- DR9 Quasar Absorption Line Catalog
  - Projected identification of ~100,000 metal absorption systems by survey completion (Lundgren et al., in prep.)
Mining Metals in the BOSS Quasar Spectra
Britt Lundgren (Wisconsin), Don York (UChicago), Yusra AlSayyad (Washington)
+Project 37 co-authors, and the SDSS-III Collaboration

Metal absorption line catalogs for the VAC5 quasars - modeled on DR7 database (York et al. 2012, in prep)

BOSS DR10 database now online. feedback welcome!
Continuum-subtracted spectra and absorption line catalogs for each quasar spectrum will be released in parallel with the DR10 Quasar Catalog (Summer 2013).

$z_{qso} = 1.639$

$z_{abs} = 1.164$

$z_{abs} = 1.294$

... to be released in parallel with the DR10 Quasar Catalog (Summer 2013)
QAL Detections in the SDSS-III BOSS Survey
Credit: Mark SubbaRao (Adler Planetarium, Chicago)
Luminous Red Galaxies vs. MgII Absorbers
Mg II Dark Matter Halos at z~0.6

- Cross-correlations with LRGs reveal a (weak) anti-correlation between Mg II equivalent width and DM halo mass at z~0.6  

\[
<\log M> \sim 11.3 \pm 0.5 \\
<\log M> \sim 12.7 \pm 0.7
\]
Evolution of Mg II Dark Matter Haloes

- Clustering can also constrain models of dark matter halo mass and gas radius evolution

- So far, Mg II clustering is consistent with a non-evolving DM halo mass (Lundgren et al. 2011; Tinker, Lundgren, Wake, et al. in prep.)
Interpretation of the W - M Anti-Correlation

- If not virialized gas in massive halos, then what’s producing the large widths in these multi-component absorbers?

Super-winds from star formation?
(Prochter et al. 2006; Bouche et al. 2006; Murphy et al. 2007; Nestor et al. 2010)

- Trend only observed at high-z
  - observational bias?
  - galaxy evolution?
Mg II Absorbers as Tracers of Star Formation

- MgII EW correlated with star-formation? (Zibetti et al. 2005)
Mg II Absorbers as Tracers of Star Formation

- Quasar sight lines with Mg II intervening absorption found to contain dust

(York et al. 2006)
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\[ \text{observed } E_{B-V} \] vs. \[ W_0 \] [Å]

\[ \text{[OII] line luminosity } [10^{40} \text{ erg/s/Å}] \] vs. \[ \lambda \] [Å]

(Ménard et al. 2008)

(Ménard et al. 2009)
Mg II Absorbers as Tracers of Star Formation

The [OIII] luminosity function predicted from dNdW/dz of MgII absorbers traces the global star formation history (Ménard et al. 2009)
“Smoking Gun” Evidence of Outflows?

- Mg II absorbers can account for as much as 50% of the dust expelled from galaxies (Ménard & Fukugita 2012)
“Smoking Gun” Evidence of Outflows?

- Absorption stacks from galaxies probing 4,000 galaxies in zCOSMOS (Bordoloi et al. 2011)
Direct Observations of Mg II Host Galaxies

- **3D-HST Survey** *(van Dokkum et al. 2011; Brammer et al. 2012)*
  - 248 Orbit HST Program
  - WFC3 (G141 grism and F140W direct) and ACS (G800 grism and F814W)
  - 600 arcmin²; ~10,000 galaxy redshifts at 1 < z < 3; Δz/(1+z)~0.4%
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Advantages of HST grism data for QAL science:

- high sensitivity, resolving power
- capable of resolving faint galaxies in close proximity to quasar sight lines
- large FOV for this depth
A census of quasar absorption lines with $W > 0.4\,\text{Å}$ in the KTRS DEIMOS spectrum reveals three strong ($W_r > 0.8\,\text{Å}$) multi-ion Mg II systems in the range $1 < z < 2$. 

**Census of Quasar Absorption Lines in 3D-HST**

$z_{\text{QSO}} = 2.5946$

$z = 1.357$

$z = 1.241$

$z = 1.744$
• Each identified Mg II absorption system matches to an isolated galaxy at 1 < z < 2 identified with 3D-HST G141 grism observations with:
  • $\Delta z < 0.004$
  • $20 < \rho \text{ (kpc)} < 60$
• The spatial extent of line emission rules out a dominant contribution from an AGN

Lundgren et al. 2012
**Properties of the Mg II host galaxies:**

- \( \log (M/M_\odot) \sim 9.75 \)
- SFRs > 5 \( M_\odot / \text{yr} \)
- \( \Sigma \text{SFRs} > 0.3 M_\odot / \text{yr} / \text{kpc}^2 \)
  consistent with local starbursts and LBGs, sufficient to launch large-scale winds
- Evidence for SF-driven outflows reaching distances of at least 60 kpc around galaxies
- Suggests prolonged SF over > 150 Myr

Lundgren et al. 2012
The data indicate no strong evolution in the $W-q$ relation from $z \sim 2$.
WFC3/IR Grism Observations of High-z Mg II Host Galaxies

- An evolving azimuthal distribution of Mg II around star-forming galaxies from z~2.
- Consistent with an increasing collimation of outflows with time (Law et al. 2012)

Lundgren et al. 2012
• New large absorber catalogs from the SDSS have dramatically changed our understanding of quasar absorption line origins in the past 5 years
  • **Stacking analyses** suggest that Mg II is a cosmic star formation indicator
  • **Clustering analyses** determined the typical Mg II environments and halo masses, leading to a better understanding of galaxy halo evolution to $z \sim 2$.

• **Direct, unbiased detections of Mg II host galaxies at $z>1$** from 3D-HST indicate that high-EW Mg II traces large-scale outflows from starbursting galaxies.

• New large overlapping surveys of absorbers and galaxies are on the horizon (eBOSS, PFS?), which will allow for better measurements of
  • galaxy-absorber correlations, the evolution of the IGM from $z \sim 5$... more!