The Physics of Extragalactic Gas: One Argument for a
Next Generation Space Telescope

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Abstract. Observations of the Galactic ISM have had tremendous impact on our understanding of the physics of galactic gas and the processes of galaxy formation. Similar observations at $z > 2$ reveal the neutral baryonic content of the universe, trace the evolution of metal enrichment, shed light on process of nucleosynthesis and dust formation, and yield precise measurements of galactic velocity fields. Owing to the limitations of UV spectroscopy, however, researchers are unable to examine galactic gas at $0 < z < 2$, an epoch spanning $\approx 80\%$ of the current universe. To complement the multitude of ongoing programs to identify and research $z < 2$ galaxies, a next generation space telescope is essential to investigate the gas which feeds and records the history of galaxy formation.

1. What is the Problem?

In the next decade, numerous observational programs will identify and investigate overwhelming numbers of $z < 2$ galaxies. These surveys will characterize the history of star formation, the evolution of galaxy morphology, and the assembly of large-scale structure. Altogether, these efforts are likely to revolutionize our view of stars and galaxies at $z < 2$. In contrast to these achievements, these observations will have minimal impact on our understanding of the gas which feeds star formation. At all redshift, gas is the major baryonic component of the universe and, at $z > 1$, probably the dominant baryonic component of most galaxies. The principal challenge associated with examining the physics (e.g. metallicity, density, ionization state, temperature) of this gas is that the majority of diagnostics lie within the ultraviolet (UV) pass-band. To cover this epoch, one requires a next generation space telescope.

With the advent of echelle spectrographs on 10m-class optical telescopes, researchers have pursued quasar absorption line (QAL) studies at unprecedented levels in the early universe. These observations have revolutionized our understanding of the Ly$\alpha$ forest (e.g. Miralda-Escudé et al. 1996; Rauch 1998), measured the baryonic density of the universe (Burles & Tytler 1998; Rauch et al. 1997), revealed metals in among the least overdense structures observed (Tytler et al. 1995; Ellison et al. 2000), provided new insight into the chemical enrichment history of the universe (Pettini et al. 1997; Prochaska & Wolfe 2000), and traced the velocity fields of protogalaxies (Prochaska & Wolfe 1997). These studies have tremendous impact on our theoretical description of gas in the early universe. For example, aside from the CMB, comparisons of CDM predictions

arXiv:astro-ph/0208143v1 6 Aug 2002
with the Lyα forest stand as one of the greatest successes of this cosmological paradigm. Furthermore, the majority of theorists at this workshop stressed one particular point: advances in ‘gastrophysics’ are essential to addressing the next theoretical frontier. Empirical constraints on ‘gastrophysics’ can only be made through observations of gas and QAL observations provide the most efficient avenue of investigation.

In contrast with the $z = 2 - 5$ universe, there are very few diagnostics of the IGM or extragalactic ISM at $z < 2$. This antithesis is easily explained: the majority of physical diagnostics have observed wavelengths below 3000Å at $z < 1.5$. In particular, the Lyα transition (at 1215Å, the reddest HI resonance line) can only be observed at $z > 1.6$ with optical spectrographs. Without coverage of this key transition, one cannot begin to address the preceding list of scientific inquiry.

An extragalactic observer like myself might be prone to nonchalantly dismiss the $z < 2$ universe. After all, this represents only 25% of the redshift path accessible to QAL analysis. This perspective, however, is horribly skewed. The epoch spanning $z = [0, 1.5]$ encompasses roughly 80% of the current age of the universe. If one considers the temporal evolution of any quantity (e.g. chemical enrichment, galaxy clustering, luminosity functions), then to overlook this epoch is to remain ignorant of the universe.

In this brief proceeding – written in support of a next generation UV telescope – I will emphasize the preceding introduction through a review of one major area of QAL research: the damped Lyα systems (DLA). These QAL systems are defined to have an HI surface density in excess of $10^{20.3}$ cm$^{-2}$ and they dominate the universal HI content at all epochs following reionization. At $z > 2$, the DLA are believed to be the progenitors of present-day galaxies (Kauffmann 1996; Steinmetz 2002) and echelle observations of the sightlines penetrating these galaxies provide detailed physical measurements of the protogalactic ISM. The measurements include chemical enrichment level, star formation rate, dust content, nucleosynthetic enrichment history, as well as clues to the pressure, temperature, and ionization balance of this multi-phase medium. These observations are directly analogous to observations of the Galaxy, LMC, and SMC carried out by HST and past UV telescopes.

This is the central thesis of this proceeding: current observations reveal the physics of galactic gas locally and at $z > 2$ but very rarely address the $\approx 10$ Gyr in between. To probe what amounts to 80% of the universe, one needs a next generation space telescope. In the following, I will highlight some of the major results of research on damped Lyα systems, primarily those related to my own research with optical echelle spectrographs. To pursue these same research areas at $z < 2$ will require similar instrumentation in the UV pass-band.

2. **What We Would Like to Pursue at $z < 2$**

2.1. **HI and Metal-Enrichment**

Damped Lyα systems derive their name from the observed quantum mechanical damping of the Lyα transition relating to their very large HI column densities, $N$(HI). Because the Lyα profile is dominated by this damping, a standard fit to the observed profile has two free parameters: (i) the centroid or $z_{abs}$; and
Figure 1. Evolution in the cosmological HI density of the universe $\Omega_{DLA}$ in units of critical density as derived from DLA observations. Note in particular, the large uncertainties in $\Omega_{DLA}$ at $z < 1.7$ (solid squares and triangle) and the large offset between these two UV surveys (IUE: Lanzetta, Wolfe, & Turnshek 1995; HST: Rao & Turnshek 2000). These uncertainties highlight the inability of current UV spectrographs to address this fundamental measure.

(ii) $N$(HI). Accurate measures of $N$(HI) can be acquired with modest resolution and S/N. Wolfe and his collaborators initiated surveys for these galaxies 20 years ago (e.g. Wolfe et al. 1986; Storrie-Lombardi & Wolfe 2000) and the majority of research has been performed on 4m-class telescopes. Figure 1 summarizes the principal result from these HI surveys: the cosmic evolution of $\Omega_{DLA}$, the universal mass density of neutral gas in units of the critical density. Focus on the measurements at $z < 2$ which were derived from IUE data (solid triangle; Lanzetta, Wolfe, & Turnshek 1995) and HST follow-up observations of a MgII-selected sample (solid squares; Rao & Turnshek 2000). The uncertainties in each set of measurements are very large (those are logarithmic error bars!) and one notes a stark disagreement between the central values of the two surveys. These uncertainties emphasize the current challenge of studying HI gas at $z < 2$ with existing UV spectrographs. While COS+HST will enable a modest survey of DLA at $z < 0.6$, the parameter space $z = [0.6, 1.7]$ will require a next generation space telescope.

Aside from the HI content, the most basic measure of the galactic ISM is metallicity. Because of the large HI surface density of DLA, ionization corrections are small and measurements of low-ions like Fe$^+$, Si$^+$, and Zn$^+$ yield accurate measures of the metallicity, i.e., $[\text{Zn}/\text{H}] \approx [\text{Zn}^+/\text{H}^0]$. The only serious systematic error is dust depletion; refractory elements like Fe and Si might be depleted from the gas-phase such that $\text{Si}^+/\text{H}^0$ and $\text{Fe}^+/\text{H}^0$ are lower limits to the true metallicity. In general, the depletion levels of the DLA are small (Pet-
Figure 2. Metallicity measurements for \( \approx 50 \) DLA at redshift \( z \approx 2 - 4.5 \). Overplotted are the HI-weighted and unweighted means in several redshift bins. Interestingly, one observes minimal evolution in these mean metallicities. Of particular interest, is resolving how the gas chemical enrichment evolves from \( z = 2 \) to today.

Metallicity observations of a large sample of DLA present two main results: (1) an \( N(\text{HI}) \)-weighted mean \( < Z > \) which is the cosmic mean metallicity of neutral gas; and (2) metallicities for a set of galaxies which presumably span a large range of mass, morphology, and luminosity.

Figure 2 presents over 50 metallicity measurements from \( z \approx 2 - 4.5 \) (Prochaska & Wolfe 2002). These are the principal results: (1) the mean metallicity (weighted or unweighted) is significantly sub-solar; (2) there is little evolution in the mean metallicity over this redshift range with the possible exception of a modest decrease at \( z > 3.5 \); (3) no galaxy exhibits a metallicity lower than 1/1000 solar. These optical observations constrain models of chemical evolution at these epochs (e.g. Pei, Fall, & Hauser 1999) and give the first glimpse into metal production in the early universe. It is crucial, however, to press to lower redshift. The time encompassed by the redshift interval \( 2 < z < 4.5 \) pales in comparison with \( z < 2 \). Of immediate concern is to determine how the mean metallicity rises to the enrichment level observed today.

### 2.2. Relative Abundances: Dust and Nucleosynthesis

High resolution \( (R > 30000) \), high \( S/N \) \( (> 30 \text{ res}^{-1}) \), observations of the damped Ly\( \alpha \) systems enable detailed studies of nucleosynthetic enrichment and dust properties in the early universe. This level of data quality is crucial to achieving the better than 10% precision required by relative abundance studies. Currently, there is an entire 'cottage industry' focused on this area (Lu et al. 1996; Prochaska & Wolfe 1999; Molaro et al. 2000; Pettini et al. 2000; Ledoux, Berg-
Figure 3. Relative abundances of (a) Si/Fe and (b) N/α versus Si/H and α/H where α refers to either Si or S for the DLA. The upper panel highlights the competing effects of nucleosynthesis and dust depletion in interpreting gas-phase abundances. We currently interpret the plateau of [Si/Fe] at [Si/H] < −1.5 as the result of Type II SN nucleosynthesis and are confident the rise in Si/Fe at [Si/H] > −1 is associated with differential depletion (Prochaska & Wolfe 2002). UV observations would allow one to trace these two processes at z < 2. The lower panel compares DLA (circles and triangles; the latter are upper/lower limits) against N/α measurements for z ∼ 0 H II regions and stars (Prochaska et al. 2002; Henry, Edmunds, & Köppen 2000). Although the majority of DLA lie on the N/α plateau observed in metal-poor H II regions, a significant sub-sample is identified at N/α < −1. This sub-sample is cautiously interpreted by Prochaska et al. (2002) as evidence for a truncated or top-heavy IMF. N/α observations at z < 2 would help reveal the timescales of SF and the nature of the IMF at...
eron, & Petitjean 2002). Figure 3 presents two of the principal results from our efforts: (a) [Si/Fe] and (b) [N/α] measurements against [Si/H] metallicity.

The super-solar Si/Fe ratios presented in panel (a) highlight the greatest obstacle to interpreting relative abundance measurements from gas-phase abundances: the competing effects of nucleosynthetic enrichment and differential depletion. In terms of dust depletion, one observes Si/Fe enhancements in depleted gas owing to the differential depletion of these two refractory elements. Regarding nucleosynthesis, Si/Fe enhancements suggest Type II SN nucleosynthesis (e.g. Woosley & Weaver 1995) whereas solar ratios would imply Type Ia SN enrichment patterns. Currently, we interpret the plateau of Si/Fe values at low metallicity as the primary result of nucleosynthesis. The mean enhancement matches the Galactic halo-star observations at the same metallicity (e.g. McWilliam 1997) and it would be difficult to understand why differential depletion would imply such a uniform enhancement. In contrast, the rise in Si/Fe at [Si/H] > −1 is highly suggestive of differential depletion. One expects a decrease in Si/Fe from nucleosynthesis at higher metallicity due to the increasing contribution from Type Ia SN and larger depletion levels are sensible in a higher metallicity ISM. Investigating evolution in abundance ratios like these at z < 2 would reveal the detailed enrichment history of galaxies and the evolution of dust formation.

Overcoming this dust/nucleosynthesis degeneracy is among the most active areas of DLA research. One avenue is to focus on special pairs of elements which are especially sensitive to only one effect. Panel (b) is an excellent example of this; plotted are N/α pairs from a recent analysis by Prochaska et al. (2002). For N, S, and Si (the latter two are α-elements), depletion effects are small and the results show the nucleosynthetic history of N in the DLA. For comparison, we also plot [N/α], [α/H] pairs for z ∼ 0 H II regions and stars (see Henry, Edmunds, & Köppen 2000). The majority of DLA observations fall along the locus of local measurements, in particular the plateau of N/α values at [Si/H] < −1. In contrast, a sub-sample of low metallicity DLA exhibit much lower N/α values which Prochaska et al. (2002) interpret these in terms of a truncated or top-heavy IMF. These observations have important implications for the processes of star formation in the early universe and measurements at z < 2 would assess the timescale of star formation in these galaxies and further elucidate the nucleosynthesis of nitrogen.

2.3. Star Formation

Through observations of the C II* 1335 fine-structure transition, it is possible to infer the star formation rate per unit area (SFR/area) within DLA. In the Milky Way, the dominant cooling mechanism of the ISM is [CII] 158 μm emission from collisionally excited C + (Wright et al. 1991). Assuming steady-state equilibrium and that star formation dominates the ISM heating, one can infer the SFR/area from observations of N(CII*)/N(HI) (Wolfe, Prochaska, & Gawiser 2002). In practice, the technique is complicated; one must self-consistently solve for the two-phase medium of the ISM and address several dust-related issues. Nevertheless, the method allows for an assessment of the SFR/area of the DLA and thereby the SFR density ˙ρ∗ of these protogalaxies. Figure 4 presents a preliminary picture of the SF history of the DLA assuming a two-phase medium with
cooling dominated by the (a) CNM and (b) WNM. The two sets of data points with error bars in each panel are the DLA measurements for two assumptions of dust depletion, the solid points are $\dot{\rho}_s, z$ pairs from other surveys (Steidel et al. 1996; Treyer et al. 1998), and the solid and dashed lines are assumed fits to the DLA data. Because limits on integrated light (e.g. Bernstein, Freedman, & Madore 2002) rule out the WNM solution, focus on the rates for the CNM. Our observations suggest $\dot{\rho}_s, z$ values consistent with or somewhat lower than those inferred from LBG observations. Understanding the connection between these two galactic populations will be very important for resolving the history of galaxy formation. One can apply these same techniques at $z < 2$ with UV spectroscopy. The results would offer a complimentary assessment of the SFR from emission-line and integrated light techniques. These SF diagnostics are critical for deciphering the build-up of galactic structure and metal enrichment in our universe.

2.4. Velocity Fields, $\alpha$, etc.

The space allotted for this proceeding precludes a full discussion of the impact of a next generation UV telescope on even DLA research. To list a few areas I will neglect: (1) velocity fields: measurements of the gas dynamics in DLA yield mass estimates in a fashion which avoids the luminosity-bias of most traditional approaches (Prochaska & Wolfe 1997). Gas dynamics are sensitive to non-gravitational motions (e.g. SN feedback), however, and interpretation may not be straightforward. Nevertheless, comparisons of QAL velocity widths with stellar measures would lend further insight into measuring galactic masses; (2)
H2: With far-UV spectroscopy, one can examine molecular hydrogen in the DLA (e.g. Bechtold 2002) and thereby examine the gas which serves as the precursor to star formation. Additionally, one gains insight into dust formation and several physical characteristics of the gas (e.g. temperature, UV radiation field); (3) α: observations of DLA at \( z > 2 \) have enabled an analysis of the evolution of the fine-structure constant (e.g. Murphy et al. 2001) and have implied possible variations in this fundamental physical constant. UV observations would allow us to perform a similar inquiry at \( z < 2 \).

3. What We Want or What We Need

The resolution and S/N needed to examine the DLA or perform QAL studies in general is dependent on the specific research area. Nevertheless, we can lean on our extensive experience with high \( z \) QAL observations using optical spectrographs. For the majority of scientific applications, \( R = 30000 \) is a bare minimum. Only at this resolution can one confidently distinguish Lyα clouds from metal-lines in the Lyα forest, obtain abundance measurements to greater than 0.1 dex precision, resolve velocity fields, and investigate a multi-phase medium. Note this value is 50% greater than the \( R = 20000 \) of COS+HST. I fear this instrument will have limited impact on several important research areas, e.g., relative chemical abundances, kinematic characteristics.

Regarding S/N, a good lower limit is 30 per resolution element (i.e. 15 pix\(^{-1}\) for 4 pixel sampling). At this level, one can carefully address systematic errors like continuum placement and also analyse a wealth of very powerful absorption line diagnostics (e.g. Si II 1808, C IV 1550, O VI 1030). As always, one gains by achieving higher S/N and many applications would depend on higher sensitivity.

Now, consider wavelength coverage. For the majority of QAL research, coverage from Lyα (1215Å) to 2000 Å rest-frame is essential. Many projects (e.g. D/H measurements, photoionization assessment, H2 observations) need coverage down to 1000 or even 900 Å rest-frame. It is my opinion that an instrument providing coverage from 1100–3200 Å would be ideal with 1200–3000 Å acceptable.

Finally, and perhaps most importantly, observing power. To allow observations of a large enough sample of QSO’s at \( z < 2 \), a UV telescope must achieve the above resolution, S/N, and wavelength coverage for a \( V \approx 18 \) QSO in a reasonable exposure time (\( < 10 \) hr). This would provide enough targets to examine the physical conditions at similar levels as achieved at \( z > 2 \). Taking the predicted performance of COS+HST as a starting point, the next generation space telescope would need a 5–10× improvement over COS+HST in its highest throughput pass-band (1100–2000Å) and an increase of 50× over COS+HST at \( \lambda > 2000\) Å. Although improvements in coatings and instrument design could make-up 3× of the difference (probably over 10× at \( \lambda > 2000\) Å), a larger aperture telescope is unavoidable. After attending this workshop, I feel a 4m aperture might just satisfy the constraints I have laid out and a ≥ 6m aperture would certainly meet the demands. Obviously, this will require terrific funding from NASA and, therefore, considerable support from the astronomical community. I am convinced, however, that the value of examining the gas physics of the universe at \( z < 2 \), an effort which complements numerous observational programs within NASA’s ORIGINS and SEU Themes, is worth the expense.
Acknowledgments. I would like to thank S. Rao and A. Wolfe who provided the HI and C II* figures. I also wish to apologize to the many folk in the DLA and ISM community who I failed to reference in this brief proceeding.

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