The following are recent results arising from research carried out with my collaborators.

**Star Formation Rates in Damped Ly\(\alpha\) Systems**

I have developed a new technique based in HIRES observations that yields the heating rate of neutral gas in damped Ly\(\alpha\) systems (DLAs), and from that the star formation rate per unit comoving volume. Until now, comoving star formation rates have been obtained for highly luminous objects such as the Lyman Break Galaxies. My technique measures rates in objects more representative of the protogalactic mass distribution and at redshifts currently inaccessible to the Lyman Break Technique.

![Graph](image)

Figure 1: Star formation rate per unit comoving volume versus \(z\) for Einstein de-Sitter cosmology with \(h = 0.5\). Red circles denote galaxies detected in emission. Green (magenta) points and error bars denote DLAs for the CNM (WNM) solutions. Blue and cyan curves are fits to the emission and the CNM and WNM points respectively. The CNM solution is more likely since the WNM case produces more background radiation than observed.

The idea - based on the heating mechanism for the ISM - is as follows: Massive stars that form in the DLA neutral gas emit far UV radiation that illuminates dust grains in the gas. Some of the incident photon energy goes into photoejected electrons which then heat the gas. In this case, the heating rate per nucleon, \(\Gamma_d \propto (D/G)\epsilon J\), where \(D/G\) is the dust-to-gas ratio and \(\epsilon\) is the heating efficiency. In a plane parallel layer, the mean intensity of far UV radiation, \(J\), is proportional to \(\dot{\psi}_s\), the star formation rate per unit area. Since \(\epsilon\) is well determined, we can measure \(\dot{\psi}_s\) provided we know \(D/G\) and \(\Gamma_d\). I measure \(\Gamma_d\) by equating it to the cooling rate. This is inferred from the C II* absorption line which measures the population of the excited \(P^{2}_{3/2}\) fine-structure state. By measuring cooling rates in about 30 DLAs and by equating the dust-to-gas ratio to the metallicity, [Fe/H], I find that the star formation rate per unit area is similar to that in our galaxy (\(\log \dot{\psi}_s = -2.4 \text{ M}_\odot \text{kpc}^{-2} \text{yr}^{-1}\)). I then use DLA statistics to deduce the comoving star formation rate \(\dot{\rho}_s\). Figure 1 shows that \(\dot{\rho}_s\) for DLAs is similar to \(\rho_s\) for Lyman Break Galaxies if the DLA gas is in the cold neutral medium (CNM). The warm neutral medium (WNM) case is probably ruled out because the higher
star formation rates result in too much background radiation. I am currently considering the many implications of this result. One of these is that the the value of \( \rho \) implies that the mass of metals accumulated by \( z \approx 2.5 \) is higher than observed in DLAs.

- **Metallicity Evolution**

![Graph](image)

Figure 2: \([\text{Fe/H}] \) vs. \( z \). Red squares are data points taken with HIRES. Blue circles are column-density weighted mean, \( < Z > \), for redshift bins discussed in text. Green points are data taken with ESI.

Figure 2 summarizes our most recent results on the metallicity evolution of DLAs. The Figure shows Fe abundance \(( [\text{Fe/H}] \) is the logarithmic abundance of Fe with respect to H normalized to solar abundance) versus redshift. The size of each data point is proportional to \( \log N(\text{H I}) \) to indicate the relative contributions to \( < Z > \), the column density weighed mean \([\text{Fe/H}] \). We measure \( < Z > \) since it equals the ratio of the comoving density of metals to that of hydrogen. Figure 2 indicates a very mild evolution of the metallicity of protogalaxies. Dividing the data into two redshift bins \( z_{\text{low}} = [1,5,3] \) and \( z_{\text{high}} = [3,4,5] \), we find no statistical difference between \( < Z (z_{\text{low}}) > \) and \( < Z (z_{\text{high}}) > \). On the other hand there is a slight evolution in the unweighted mean \([\text{Fe/H}] \). In any case the constancy of \( < Z > \) with redshift is at variance with the predictions of most chemical evolution models which predict stronger evolution in \( < Z > \). Furthermore, I note that out of the 41 objects in Figure 2, none has \([\text{Fe/H}] \) \(< -2.7 \). This is true even though we could have measured \([\text{Fe/H}] = -3.5 \) in most DLAs. Whether this “floor” is a function of population III pre-enrichment is a matter for debate.

- **Kinematics of DLAs**

We have studied the kinematics of the neutral and ionized gas in DLAs by obtaining accurate HIRES velocity profiles of low ions such as Fe II and high ions such as C IV.
The results of our work are summarized in Figure 3. This compares the low-ion with high-ion velocity profiles. Our statistical analysis supports the visual impression that the ionized gas and the neutral gas comprise distinct kinematic subsystems. This is indicated by the misalignment in velocity space of the narrow components that make up the velocity profiles, and the difference between the widths of the velocity profiles. However, despite their differences, the kinematic subsystems are interrelated as indicated by a statistically significant C IV versus low-ion cross-correlation function. Moreover, the velocity widths of the C IV profiles are ≥ to the low-ion widths in 29 out of 32 cases. This indicates the two systems are in the same gravitational potential well. We have used these results to test the standard scenario in which the high-ion (ionized) gas undergoes radial infall into dark matter halos containing centrally located rotating disks comprising the low-ion (neutral) gas. Neither the CDM nor passive evolution models predict kinematics that are consistent with all our kinematic tests. The main problem is that the models fail to reproduce the significant amplitude of the C IV versus low-ion cross-correlation function. We are currently testing new models in which the infalling ionized gas has the same angular momentum per unit mass as the collapsed neutral gas. In principle this should increase the correlation between the velocity fields of the two components.

![Figure 3: Velocity profiles of high-ions (dark lines) and low ions (light lines) in 32 separate DLAs](image)

- **Survey for Lyman-Break Galaxies Correlated with DLAs**

  The $z \sim 4$ phase of this project is now finished. We completed multi-color photometry and multi-slit spectroscopy on 3 fields toward 4 DLAs. We have doubled the number of known Lyman Break galaxies (LBGs) at $z \sim 4$. Our efficiency in finding LBGs was improved through the use of photometric redshifts. However, the sample is still too small to measure either the 2 point correlation function for LBGs or the cross-correlation function between LBGs and DLAs at these redshifts. So far the LBG two-point correlation function has only been measured at $z \sim 3$.

- **Possible Detection of Cosmological Evolution of the Fine Structure Constant**

  Using high-resolution spectra of metal lines obtained with Keck I HIRES spectrograph my collaborators and I have searched for time variability of the fine structure constant, $\alpha$. 
Variations in $\alpha$ would lead to detectable shifts in the rest wavelengths of redshifted UV resonance lines such as those used to deduce kinematics and metallicities in DLA's (e.g. Ni II, Cr II, Zn II, etc). For relativistic fine structure splitting in alkalai-type doublets, the separation between the lines is proportional to $\alpha^2$, so that small relative variations in the separation are proportional to $\alpha$. We used a new technique which is more sensitive than the alkalai technique, since it is not restricted to transitions with respect to the same ground state. Rather it compares transitions relative to different ground states in different species. Using species with widely differing atomic masses produces an increase in sensitivity because the difference between ground-state relativistic correction can be large and of opposite sign. We measure variations in $\alpha$, i.e. $\Delta \alpha/\alpha = (\alpha_{e}/\alpha) - 1$, by explicitly including these variations in a Gauss-Newton optimization code in which other parameters such as velocity width and thermal width of the absorption lines are allowed to vary freely. The results based on 72 quasar absorption systems are summarized in Figure 4. The figure shows possible evidence that $\Delta \alpha/\alpha$ decreases with $z$.

This is a potentially exciting results that needs to be checked with independent data sets. We have searched for possible systematic errors and find that removal of the most important of these, atmospheric dispersion and isotopic abundance evolution, would enhance

**Results**

**Sample at present:**
28 MgII/FeII absorption systems towards 17 QSOs (Churchill)
18 DLA absorption systems (+ 3 further Mg/Fe systems) towards 13 QSOs (Prochaska/Wolfe)
21 SiIV doublets towards 13 QSOs (Prochaska/Wolfe)
All Keck spectra, $<s/n> \sim 30$/pixel, resolution FWHM $\sim 7$ km/s for whole dataset

**Overall deviation from zero is 4 sigma, (uncorrected for any systematic effects)**

Figure 4: Summary of evidence for variations in $\alpha$ from Webb et al. (2001).
the significance of these results.

- **Thick Disk Abundance Patterns**

We (Prochaska et al. 2000) have obtained accurate HIRES spectra for 10 thick disk stars. Our analysis confirms previous studies of O and Mg which show enhancements of \([\text{O/Fe}]\) and \([\text{Mg/O}]\) relative to the thin disk. We also find that the elements Si, Ca, Ti, Mn, Co, V, Zn, Al, and Eu have a chemical history distinct from the thin disk. Moreover, the thick disk abundance patterns tend toward the values observed for halo stars with \([\text{Fe/H}]=-1\). This suggests that the thick disk stars had a chemical enrichment history similar to the metal-rich halo stars.

Furthermore, we find that (1) all 10 stars exhibit enhanced \(\alpha/\text{Fe}\) ratios with O, Si, and Ca exhibiting trends of decreasing overabundance with increasing \([\text{Fe/H}]\). If these trends are explained by the onset of Type Ia Sn, then the thick stars formed over the course of \(\geq 1\text{Gyr}\). This slow formation time is apparently incompatible with dissipational collapse scenarios for the formation of the thick disk. Models with heating of an initially thin disk are favored instead.

Figure 1 shows the impact of the thick disk abundances on interpretations of abundances in DLAs. The DLA abundance pattern exhibits a classic example of halo abundances with enhanced \(\alpha\)-elements and deficient Mn and normal Ni, Cr, and Al. While the \([\text{Zn/Fe}]\) ratio of DLAs is high, the overall type II Sn pattern is clearly evident. In fact there is tentative evidence for an evolutionary sequence in the abundances of DLAs to the thick disk stars.

![Figure 1: Comparison of abundance patterns of DLAs (green circles) and thick-disk stars (blue stars) from Prochaska et al. (2000).](image-url)
On the other hand, the abundance pattern is also consistent with element depletion in the ISM. This would explain the enhanced Si, Zn, and S, but is inconsistent with the Mn trend. Our guess is that the DLAs consist of a type II Sn pattern on top of a small amount of dust.