PROJECT DESCRIPTION

Abstract

The Sloan Digital Sky Survey (SDSS; York et al. 2000) offers an unprecedented chance to understand the origin(s) of the outflowing gas seen in absorption in many quasars and other active galactic nuclei. A full understanding of the process of accretion onto supermassive black holes at the centers of galaxies must encompass these outflowing "winds". These winds may carry away as much matter per year as is accreted onto the black hole, and are thus a significant dynamical component of quasars. Also, follow-up studies of absorption in quasars yield better constraints on physical conditions near the black hole than studies of emission do. This proposal will model the unabsorbed spectra of quasars using Principal Component Analysis, catalog intrinsic absorption regardless of trough width or outflow velocity using the Absorption Index (Hall et al. 2002), a refined version of the traditional BALnicity Index (Weymann et al. 1991), and use the resulting large, unbiased sample of intrinsic absorbers to understand quasar physics. Correlations between absorption and other quasar properties will be studied to confirm or reject existing predictions and, in all likelihood, to discover unexpected correlations which point the way toward improved quasar models. Furthermore, unusual quasars which are valuable targets for follow-up, or whose SDSS spectra alone can constrain physical conditions in the absorbing gas, will be identified, and a search will be conducted for BAL trough variability using repeat observations already existing within SDSS. Databases of spectral fits and measured absorption and other quasar properties will be made publicly available along with the SDSS data and catalogs.

Introduction: The SDSS and Intrinsic Absorption in Quasars

The Sloan Digital Sky Survey (SDSS) is using a drift-scanning imaging camera and two multi-fiber double spectrographs on a dedicated 2.5m telescope (Gunn et al. 1998) to image $\sim$10,000 deg^2 in five bands ($ugriz$). Spectra are being obtained for $\sim 10^6$ galaxies to $r = 17.8$ and $\sim 10^5$ quasars to $i = 19.1$ ($i = 20.2$ for $z > 3$ candidates) selected from the imaging data. Quasar candidates are targeted for spectroscopy based on color criteria (Richards et al. 2002) or because they are unresolved objects with radio emission detected by the FIRST survey (Becker, White, & Helfand 1995). The essence of the color selection is simple: target objects whose broad-band colors are different from those of normal stars and galaxies. Due to these inclusive criteria, the selection of candidates using i band magnitudes rather than blue magnitudes which are more affected by absorption and reddening, and its area and depth, the SDSS quasar survey is extremely complete even for quasars with unusual spectra, such as those with strong reddening (e.g., the SDSS identifies as quasar candidates 30 of the 31 faint ($i \simeq 21$), red, radio-selected FIRST/Deeprange quasars (White et al. 2003) with SDSS imaging), or quasars with strong intrinsic absorption (Fig. 1).

We define intrinsic absorption in quasars (used here as a generic term for luminous active galactic nuclei, or AGN) as arising from gas which forms part of the central engine, including the broad and narrow emission-line regions (the BLR and NLR). Absorption from the quasar host galaxy is sometimes defined as intrinsic, but not for the purposes of this proposal. Intrinsic absorption systems have historically been classified as either narrow or broad. Systems broader than $\sim$500 km s^{-1} are almost certainly intrinsic, while narrower systems can be either intrinsic or due to gas associated with the quasar host, neighboring galaxies, or cosmologically intervening systems.

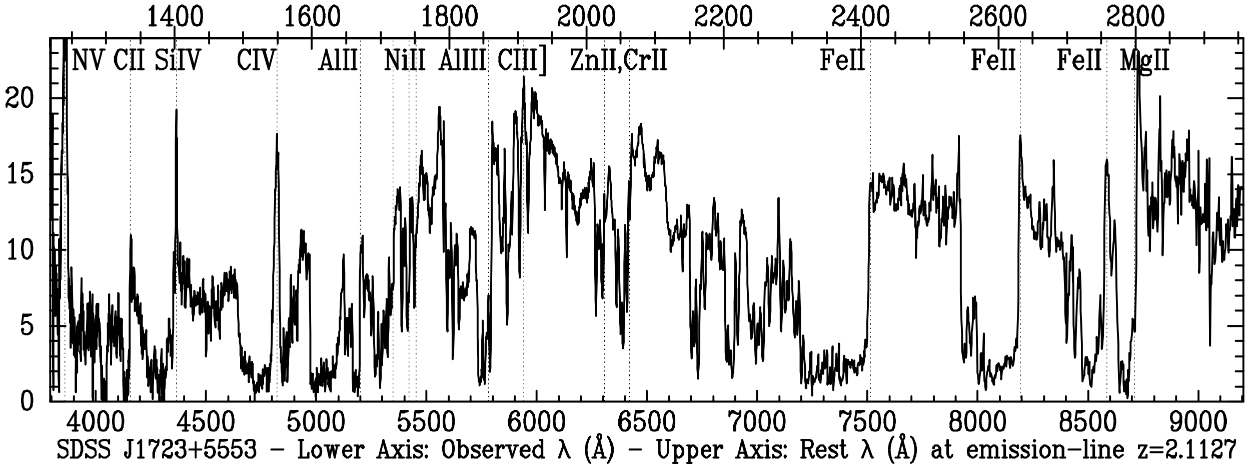

Figure 1: An extreme example of intrinsic absorption in an iron low-ionization BAL quasar.

The most dramatic cases of intrinsic absorption are the broad absorption line (BAL) quasars, with troughs $\sim$2,000$-$25,000 km s^{-1} wide outflowing at speeds up to 0.22c in the UV (Foltz et al. 1983) and $\sim$0.4c in the X-ray (Chartas et al. 2002). Usually troughs are only seen in high ionization species (HiBAL quasars), but about 15% of HiBALs also show absorption from low ionization species (LoBALs), and about 15% of LoBALs also show absorption from excited-state Fe II or Fe III (FeLoBALs). The mass rates in the outflows can be comparable to the accretion rates required to power quasars ($\sim$1 M$_\odot$/year), so a full model for quasars must explain how these outflows are generated and accelerated.

There are two prominent theories on the origin of broad intrinsic outflows. One is that they are accretion disk winds (e.g., Murray et al. 1995); the other is that they are dusty cocoons of gas surrounding young or rejuvenated quasars (e.g., Voit et al 1993). Since BAL outflows occur in $\sim \frac{1}{6}$ of quasars (Hewett & Foltz 2003; Reichard et al. 2003b), the first theory implies that such outflows cover $\sim \frac{1}{6}$ of our lines of sight to all quasars; the second implies that all quasars have such outflows for $\sim \frac{1}{6}$ of their lifetimes. Quasars with intrinsic absorption, whether BAL troughs or narrower systems, are more polarized than unabsorbed quasars (Leighly et al. 1997, Hall et al. in prep.). Thus, the scatterers must be preferentially distributed along an axis normal to the axis (or plane) of the absorbing gas (Schmidt & Hines 1999). Equatorial outflows provide such an orientation, lending support to disk wind models. On the other hand, Canalizo & Stockton (2001) have presented good evidence that low-redshift, mid-IR-selected AGN samples in galaxies with signs of recent mergers or interactions have a larger fraction of LoBAL systems. Also, Becker et al. (2000) show that radio-detected BAL quasars have a large range of radio spectral indices, suggesting that our lines of sight span a large range of angles with respect to the plane of accretion disk. Disk wind models that include MHD effects can explain that result, since they span a large range of latitudes above the disk, making them visible with a large range of orientations but still producing flattened geometries (Everett 2003). However, another Becker et al. (2000) result, that BAL quasars are more often unresolved in the FIRST survey radio maps than non-BAL quasars are, does argue that some BAL quasars are dusty cocoons.

It may very well be that both theories are correct, in that BAL outflows can arise in more than one fashion. Determining what fraction of BAL quasars are disk winds and what fraction are dusty cocoons requires a large sample of BAL quasars covering the full range of their observed properties. The SDSS can provide just such a sample.

SDSS BAL Quasar Work to Date

The SDSS Early Data Release (EDR) catalog of ∼3800 quasars (Schneider et al. 2002) yielded 224 BAL quasars (Reichard et al. 2003a), the largest single sample of BAL quasars to date. Traditionally, the unabsorbed spectrum is modelled as a power-law and a Gaussian C IV emission line. In this paper, we also performed a χ^2-minimizing fit of a composite quasar spectrum constructed from thousands of non-BAL quasars to every EDR quasar by adjusting the underlying power-law index, the observed reddening, and the normalization in selected emission-line regions, while ignoring spectral regions where strong absorption can occur. Each quasar was then searched for BAL troughs meeting the Weymann et al. (1991) definition. The traditional continuum-fitting method yields slightly fewer BAL quasars, and tends to underestimate their strengths compared to our new method.

One of the first trends searched for with the sample was evolution of the BAL fraction with redshift (Tolea et al. 2002; Reichard et al. 2003b), since the redshift range over which the SDSS can detect most BAL quasars spans the peak epoch of quasar activity at $2 < z < 3$. After correction for selection effects (Fig. 2, top), no significant redshift evolution is seen (Fig. 2, bottom). The full SDSS will provide a sample more than twenty times larger with which to detect or constrain such evolution.

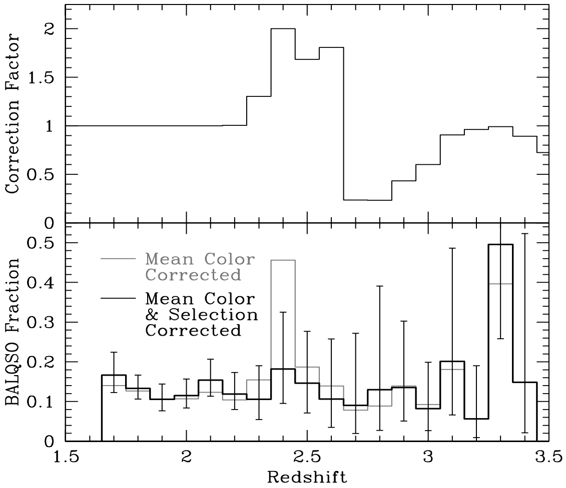

Figure 2: **Top:** the factor by which the raw BAL quasar fraction over- or under-estimates the true BAL quasar fraction due to color-dependent selection effects (Reichard et al. 2003b). The colors of quasars at $z \simeq 2.6 \pm 0.5$ are similar to those of A stars, but BAL and non-BAL quasars intersect this part of the stellar locus at different average redshifts because BAL quasars are on average redder than nonBAL quasars. The net result is that, on average, BAL quasars are easier to detect than nonBALs at $2.1 < z < 2.6$, and vice versa at $2.6 < z < 3.1$. **Bottom:** The BAL fraction as a function of redshift after correction for the above differential color selection (thin line) and after restricting the sample to those objects selected by the final SDSS quasar targeting pipeline (thick line).

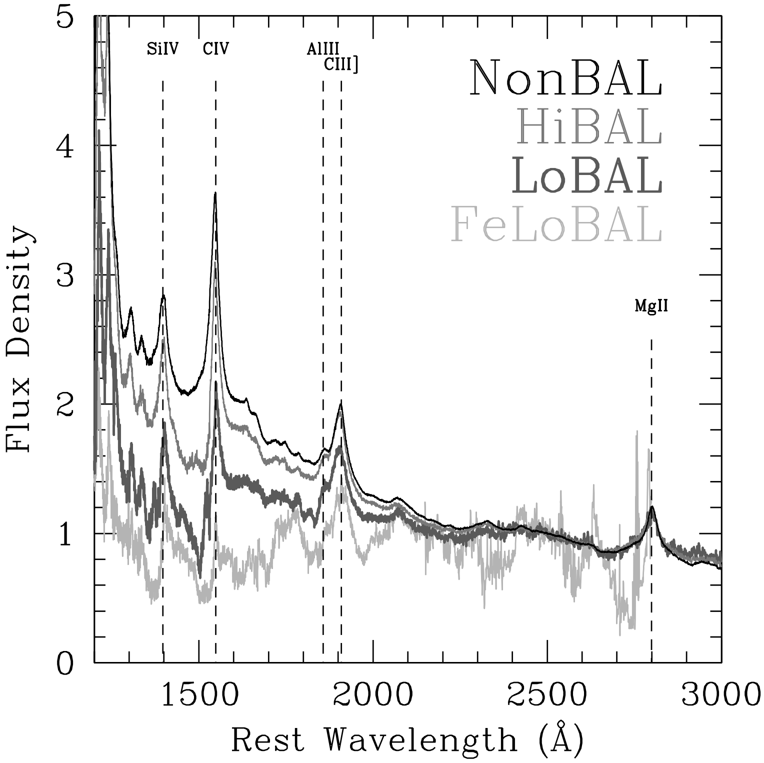

Figure 3: Composite BAL and non-BAL quasar spectra from the SDSS Early Data Release.

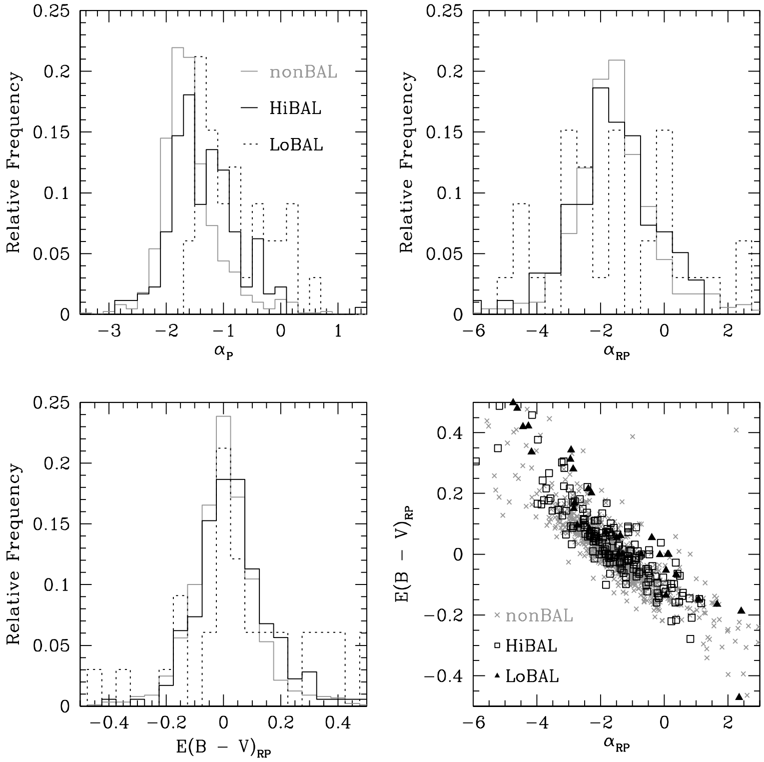

Figure 4: Results of fitting a composite quasar spectrum to non-BAL, HiBAL, and LoBAL quasar spectra, varying only the power-law spectral index α (P-fits, *top left*) or the reddening $E(B-V)$ (*bottom left*) and α (*top right*) simultaneously (RP-fits); the latter show that BAL quasars, especially LoBALs, are on average redder than non-BAL quasars (*bottom right*).

The BAL quasar population: Using complete subsamples of 153 HiBALs and 24 LoBALs, we generated geometric mean composite spectra of each subclass, which have the arithmetic mean power-law spectral index α and reddening $E(B-V)$ of the input population (Reichard et al. 2003b). Fig. 3 shows the resulting composites. Along the HiBAL-LoBAL-FeLoBAL sequence, in addition to the increasing absorption strength in C IV and other transitions, there is a clear trend for the spectra to become redder (for example, at 1600–1900 Å, where there is no strong absorption except in FeLoBALs). A natural explanation for this trend is an increasing amount of dust along this sequence. The χ^2 fitting results for BAL vs. non-BAL quasars confirm this explanation (Fig. 4, bottom right): BAL quasars span the same range of α as non-BAL quasars, but at a given fitted α, BAL quasars have larger average $E(B-V)$, despite the artifical anticorrelation introduced into their simultaneous-fit distribution because of their near degeneracy in many individual objects.

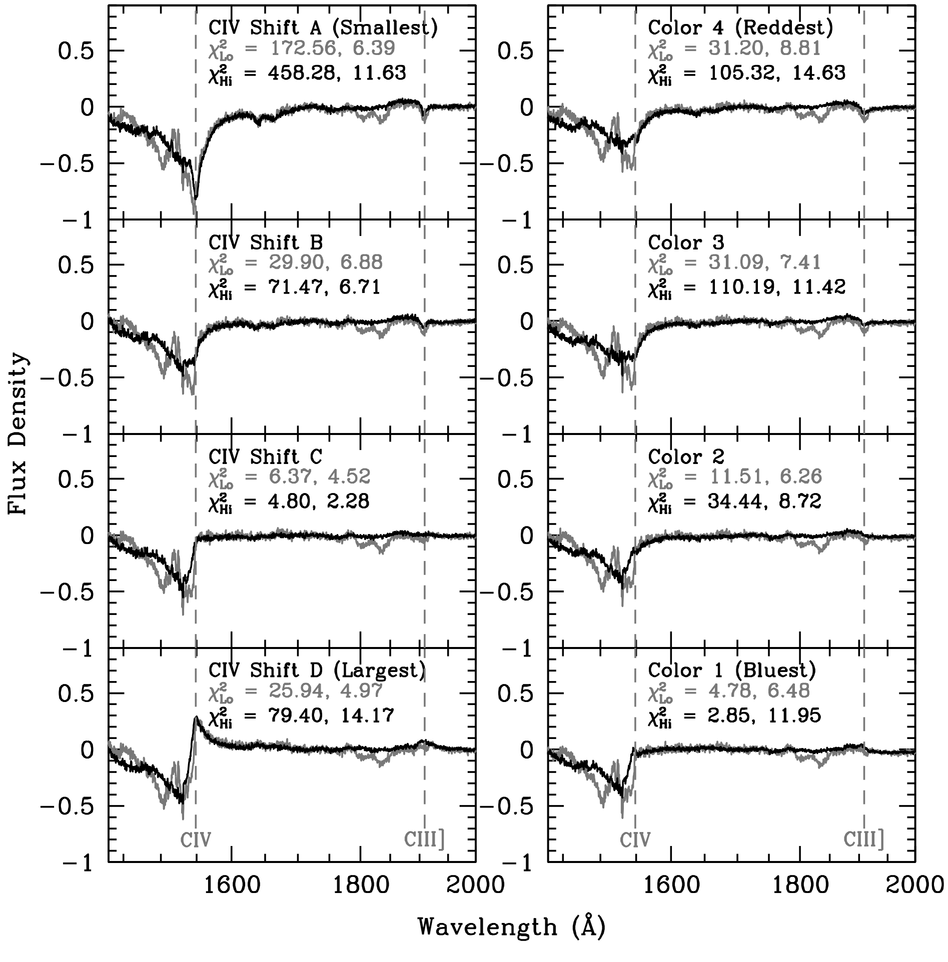

Figure 5: Difference spectra of HiBAL (*gray*) and LoBAL (*black*) composites with composites of quasars sorted by emission-line blueshift (**left**) and by broad-band color (**right**). The two χ^2 values given are for the red wing of C IV and the entire C III] emission-line region, respectively. Ignoring the region blueward of C IV, where strong absorption is present, the difference spectra indicate that BAL quasars are most similar to composites C IV Shift C **(left, second from bottom)** and Color 1 **(right, bottom)**.

Despite spanning the same range of α as non-BAL quasars, BAL quasars may have a bluer distribution of spectral indices within that range. Subtracting BAL quasar composites and composites of quasars as a function of broad-band color (Richards et al. 2002) reveals that BAL quasars best match the bluest-quartile composite (Fig. 5), as well as the second quartile of C IV emission-line blueshifts (Richards et al. 2001). That is, BAL quasars tend to have larger than average C IV blueshifts and to be intrinsically quite blue; the former trend, at least, suggests that dusty cocoon BALs are a minority — a dusty cocoon is unlikely to affect the BLR, but disk wind properties affect both emission and absorption (e.g., non-LTE accretion disk models predict bluer spectra from edge-on disks; Hubeny et al. 2000).

Unusual BAL quasars: The SDSS has also discovered individual BAL quasars worthy of in-depth study to probe the full parameter space spanned by quasar outflows (Hall et al. 2002). Examples of several classes of unusual BAL quasars have been found to date:

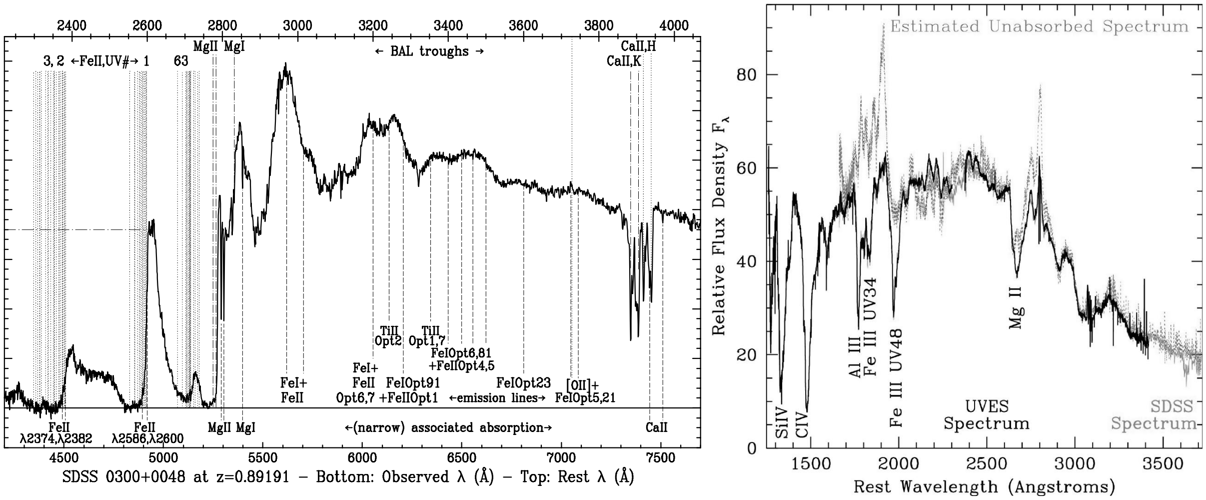

Figure 6: Two of the more unusual FeLoBAL quasars from the SDSS. **Left:** an overlapping-trough quasar with almost total absorption below 2800 Å, plus a rare Ca II outflow. **Right:** a quasar with absorption from Fe III but not Fe II (strongest line not seen at 2600 Å).

- half a dozen objects whose absorption removes up to ∼90% of all flux shortward of Mg II (Fig. 6, left). VLT 8-m telescope echelle spectra of the quasar shown, with its rare Ca II outflow, enabled us (Hall & Hutsemekers et al. 2003) to show that its outflow must be a disk wind: Ca II can only exist in gas well shielded by an H I ionization front; Ca II is only seen at the lowest line-of-sight velocities in the outflow; therefore, the lowest velocities are farthest from the quasar. This result is difficult to explain if this BAL outflow arises in a nearly spherical dusty cocoon of gas. But it is easily understood in disk wind models where the gas originating closest to the quasar is accelerated to the highest velocities, and where we can look across the direction of the outflow instead of just down along it.
- several BAL quasars with absorption from Fe III but not Fe II (Fig. 6, right), which must have high density outflows ($\log n_H \geq 10.5$ cm^{-3}) with column densities within a narrow range at a given ionization parameter, such that the partially ionized Fe II zone typical in AGN does not exist but an Fe III zone does (Hall et al. 2003). The physical parameters of most BAL outflows cannot be well constrained from low-resolution UV spectra alone, so it

is valuable to identify even rare BALs for which such constraints are possible.

- three objects with Mg II absorption extending *redward* as well as blueward of their host galaxy redshifts, possibly due to absorption of an extended continuum source by a rotation-dominated disk wind (Keck HIRES data in hand for one of the three may just barely have the SNR to confirm or refute this idea).

Lastly, for many years it was thought that BAL quasars were exclusively radio-quiet (Stocke et al. 1992), but the first SDSS BAL quasar paper confirmed the FIRST Bright Quasar Survey finding that moderately radio-loud BAL quasars exist (Menou et al. 2001).

Despite all the BAL quasar research discussed above, our understanding of quasar outflows remains limited by sample sizes (too small as yet to study trends in more than one parameter at a time) and by artificial distinctions between broad and narrow troughs (inhibiting the uniform study of trends over the full range of parameter space spanned by intrinsic absorption). A large, well-defined sample is the obvious next step.

Current SDSS BAL Quasar Work

Dr. Don Schneider (Penn State) is leading the production of catalogs of SDSS quasars accompanying each data release, an effort I am actively involved with (but not funded by). That effort includes the cataloging of traditional BAL quasars, beginning with the EDR BAL quasar catalog and analyses of composite spectra constructed from it (Reichard et al. 2003ab, discussed above), outgrowths of Mr. Tim Reichard's senior undergraduate thesis.

Another undergraduate senior at Penn State, Mr. Jon Trump, is currently working with Don Schneider, myself, and other SDSS collaborators on a catalog of ∼1500 traditionally defined BAL quasars from the SDSS DR2, a task that should be largely complete by mid-2004. We are extending the single-template fits of Reichard et al. to choosing the best-fit of multiple templates (divided by luminosity and emission-line FWHM, with nine different templates for each of three redshift bins). While this approach allows more freedom to fit the wide variety of observed quasar spectra, a potential limitation is that the freedom to change α, $E(B-V)$, and the line strengths for each template is not constrained by any observed correlations or anticorrelations among those and other quasar parameters. This may produce estimated unabsorbed spectra with global properties unlike those of quasars without absorption.

Proposed Work on Intrinsic Absorption

We will use Spectral Principal Component Analysis (SPCA; Francis et al. 1992; Shang et al. 2003; Yip et al. 2003, 2004; Vanden Berk et al. 2004) for the key step of modeling the unabsorbed spectra of quasars with intrinsic absorption. If each member of a set of input spectra is thought of as the sum of a number of appropriately weighted eigenspectra (the principal components), then Principal Component Analysis solves for the eigenspectra and the weights needed to reconstruct each input spectrum. Eigenspectra have already been constructed for a large sample of unabsorbed SDSS quasars (Yip et al. 2004). A big advantage of SPCA is that since each eigenvector includes correlated spectral properties, the spectra of quasars with absorption can be reconstructed at *all* observed wavelengths using *only* those wavelengths not affected by absorption (Connolly & Szalay 1999). The accuracy of this approach can be easily tested by excluding the same wavelength ranges for non-BAL quasars as for BAL quasars and comparing the original non-BAL quasar spectra with the PCA reconstructions based on partial spectra. Reddening from dust in intervening systems is an additional free parameter that may be required in some cases, but reddening from dust associated with the central engine may correlate with other quasar properties (as it does with the BAL trough ionization level) enough to be reproduced with PCA.

Once the unabsorbed spectrum has been reconstructed, intrinsic absorption is easily detected and characterized. The unabsorbed spectrum itself can be modeled as a power-law continuum plus individual emission lines and Fe II emission blends to measure emission-line velocity widths, continuum slope, and reddening exactly as is done for non-BAL quasars.

Sample Definition: A BAL quasar is formally defined as a quasar with a positive *balnicity index.* The BI is a modified equivalent width of C IV absorption, expressed in km s^{-1} (Weymann et al. 1991). However, this traditional BAL quasar definition excludes absorption troughs which are $\leq$2000 km s^{-1} broad or within 3000 km s^{-1} of the quasar redshift. Many such absorption systems are now known to be intrinsic (Hamann 2000), due, for example, to time-variable trough depths or partial coverage of the continuum source. (Both of those effects require that the absorption region sizes are comparable to the emission region sizes, and that the two regions are close enough to each other that absorption is seen along a significant fraction of sightlines, which places them at least within the same galaxy.)

Because of these limitations, and because it was not designed for use with spectra of the S/N and resolution of the SDSS, the balnicity index should be phased out. Instead, one can use the absorption equivalent width (e.g., Laor & Brandt 2002) or the *absorption index* (AI; Hall et al. 2002, Appendix A) to catalog and quantify absorption regardless of trough width or outflow velocity. For example, Fig. 7 shows two SDSS quasars with intrinsic absorption. One of them meets the BAL quasar definition and the other does not; but, in accord with their visual appearances, they have similar AI values. The AI thus permits more accurate study of the correlations of absorption properties with other quasar properties.

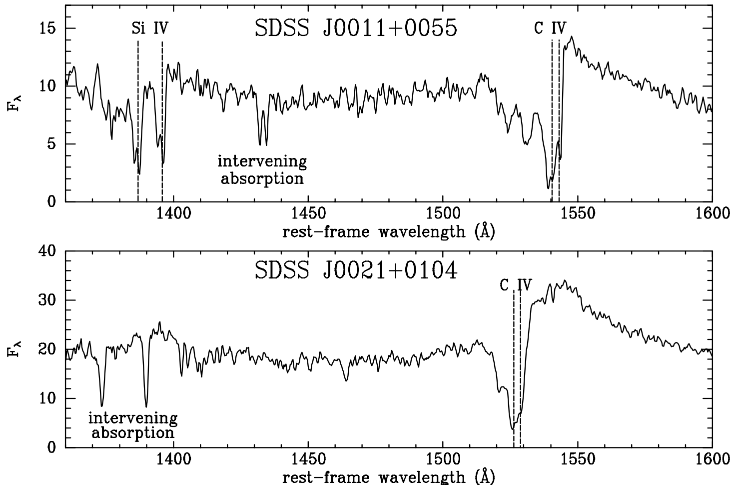

Figure 7: Example of the limitations of the traditional balnicity index (BI). The Si IV to C IV region is shown for two SDSS quasars with intrinsic absorption. The bottom quasar, SDSS J0021+0104, **is** a traditional BAL quasar, with BI = 40 km s^{-1} (Reichard et al. 2003a). The top quasar, SDSS J0011+0055 (Hutsemékers, Hall & Brinkmann 2003), **is not** a traditional BAL quasar ($BI = 0$). Despite its having broader C IV absorption than SDSS J0021+0104, and Si IV absorption as well, most of its C IV absorption is within 3000 km s^{-1} of the quasar rest frame, which is ignored in calculating the BI.

Dr. Don York (Chicago) is leading the effort to catalog narrow intrinsic absorbers ($\leq$1000 km s^{-1} broad) in SDSS quasar spectra. Between that work, ongoing traditional BAL cataloging, and this proposed work, we will catalog all candidate intrinsic absorption in SDSS quasars regardless of outflow velocity or trough width and study how absorption properties vary with other quasar properties. The proposed budget includes two person-trips to Chicago/Fermilab and two to Penn State to facilitate efficient cooperation between narrow absorption system cataloging, traditional BAL cataloging, and overall intrinsic absorption cataloging, parameter measurement, and analysis efforts.

Absorption Properties and Constraints on Models: The SDSS catalog of intrinsic absorbers should comprise $\sim$12.5% of SDSS quasars, which is perhaps half the intrinsic fraction due to our inability to detect C IV absorption at z<1.5. We can expect $\sim$3750 such quasars in the next data release, and three times that number in the full survey. Complete samples will of course be smaller, as the detectability of absorption is a function of SNR and redshift, and some confirmed quasars (especially at the faint end) are selected as serendipity targets, not by the quanitifiable quasar targeting algorithm. With this largest homogeneous sample of intrinsically absorbed quasars, we will verify the conclusions of Reichard et al. (2003b), especially that quasars are preferentially intrinsically quite blue, for both BALs and narrower systems, and measure other parameters to constrain theoretical models.

Outflows driven by radiation pressure should show a correlation of maximum outflow velocity with luminosity: $v_\infty = 60700$ km s$^{-1}\sqrt{(\frac{fL_{E,8}}{N_{22}} - 0.007M_8)/R_{17}}$, where f is the covering factor along the sightline; N_{22} is the column density in units of 10^{22} cm^{-2}; M_8 is the black hole mass in units of $10^8\,M_\odot$; $L_{E,8}$ is the luminosity in units of the Eddington luminosity for a $10^8\,M_\odot$ black hole; and R_{17} is the launch radius in units of 10^{17} cm (Hamann et al. 2002). Laor & Brandt (2002) find that the upper limit of the v_{max} distribution is indeed strongly correlated with luminosity ($v_{max} \propto L^{0.62\pm0.08}$) over the range $-26.5 < M_V < -22.5$. A correlation of v_{max}/v_{BLR} with $(L/L_{Edd})^{0.5}$ is also expected for radiatively driven winds, a trend which may also be seen by Laor & Brandt but which needs confirmation with a larger sample. We will estimate black hole masses using the Mg II line for intrinsically absorbed quasars in the redshift range $1.5 < z < 2.25$ (e.g., McLure & Dunlop 2003) and L/L_{Edd} using a standard bolometric correction, after accounting statistically for for the effects of dust extinction on the SDSS spectra. This method can introduce spurious correlations, since $L_{Edd}\propto M_{BH}\propto v_{BLR}^2$, but such correlations can be accounted for (Laor & Brandt 2002).

The correlation with covering factor f predicted above has not been tested for, nor have the joint constraints on column density and launch radius possible when the other variables are known been explored. Knowing the column density usually requires X-ray data, but the large area of the SDSS means that we will have considerable overlap with Chandra and XMM archival data. Strong deviations from the relations predicted by the above equation may be a signature of non-radiative acceleration in intrinsic outflows.

If BALs arise in disk winds driven both by radiation pressure and MHD effects (such as magnetocentrifugal acceleration along field lines threading the disk), the outflow directions in different quasars may span a range of terminal angles up to $\sim$60° above the disk, depending on the relative contributions of the two driving forces. Only when our sightline is at the outflow's terminal angle will we see its true terminal velocity and full velocity width, but those quantities' distributions will reflect the distributions of orientations, N_{22}, and R_{17}.

We will also study correlations of intrinsic absorption properties with quasar continuum and line luminosities (after correcting for dust reddening). There may be a luminosity dependence of the BAL fraction, which is 15.9±1.4% in the SDSS (Reichard et al. 2003b) but 22±4% in the on average more luminous LBQS (Hewett & Foltz 2003). A larger sample is needed to see if this effect is real or just small number statistics at the bright end. If confirmed, it may be consistent with predominantly radiatively driven winds where higher driving luminosities result in winds confined to lower latitudes. Absorption strength also correlates with intrinsic luminosity in the sample of *narrow* absorbers studied by Vestergaard (2003), but other than the tendency for Seyferts to have weaker, lower-velocity outflows, no more is known about the dependence of maximum trough width and outflow velocity on luminosity. As for line luminosity, no BAL quasars are known with strong [O III] emission, but some narrower absorption systems are seen in quasars with strong [O III]. While we can study this trend only for relatively low-redshift intrinsic Mg II absorbers, it will still be interesting to see how strong the anticorrelation between Mg II absorption and [O III] emission strength is (Brandt et al. 2000).

Besides v_{max} and the equivalent width or AI value, there are many other intrinsic absorption parameters whose statistical distributions and correlations with other parameters have rarely (or sometimes never) been studied: average and maximum covering fractions, minimum and mean outflow velocities, number of distinct troughs (both narrow and broad) plus trough widths and shapes (second and third moments) for different ions. Disk wind simulations can now predict absorption trough profiles (Proga 2003; Everett 2004), so comparison of predictions and observations can help decide which observational parameters are the best tracers of the underlying physical parameters of the outflow. But our understanding of quasar outflows is still rudimentary enough that searches should be made for more than just predicted correlations. Follow-up observations (X-ray work, polarimetry, near-IR spectroscopy etc.) can then be designed to sample the full range of BAL quasar properties.

For example, low-ionization absorption is usually deepest at the low-velocity end of the high-ionization absorption trough (Voit et al. 1993), but not always. And most troughs are deeper at low velocities than at high velocities, but not all. Are the exceptions to those trends just random outliers, or are they interesting cases of unusual outflow parameters?

Larger samples of radio-detected quasars with intrinsic absorption (available from SDSS sources detected by FIRST, NVSS, and other radio surveys) are needed to study the apparent anticorrelation of maximum outflow velocities and trough strengths with radio power, and the apparent low BAL fraction among extremely radio-loud quasars (Becker et al. 2000). These effects may arise because radio-loud quasars are also X-ray loud; greater X-ray luminosity may lead to embryonic winds becoming too ionized to produce UV absorption (Murray et al. 1998). Seyferts also lack troughs as broad and as high-velocity as seen in more luminous quasars, and Ho & Peng (2001) have suggested that Seyferts are in fact radio-loud. The same effect may be at work in Seyferts as in radio-loud quasars, or it may be a luminosity dependence, which we can test by studying the joint correlations of absorption properties with optical and radio properties.

Last but not least, we will look for redshift evolution in the frequency of low- and high-ionization absorbers, being careful to match luminosities and other sample properties over the redshift range being considered. Evolution is expected for dusty cocoon absorbers, but not necessarily for disk wind absorbers.

Absorption Systems for Detailed Follow-up Studies: As pointed out most recently by Romano et al. (2003), absorption lines can offer more powerful diagnostics of physical conditions in AGN than emission lines, albeit usually only through high-resolution spectroscopy. Bright quasars whose intrinsic absorption systems have at least some unblended troughs are most desirable for high-resolution spectroscopic work; the SDSS can provide a large sample of such objects from which to choose the most promising. In addition to such systems, we will catalog unusual absorbers:

- systems with Mg I and/or Ca II, which indicate the presence of very low-ionization gas, as those lines are not shielded from photoionization by a hydrogen ionization front.
- Fe III-dominant absorbers, which can be used to put joint constraints on the density, column density, and ionization parameter of the outflow; in narrow systems, the UV34 and UV48 Fe III triplets can be used to move beyond the standard two-parameter covering factor & optical depth model of partial covering (de Kool et al. 2002; Hamann 2004).
- He I* or He II λ1640 absorbers (only one example of the latter being known to date; Hall et al., in preparation). The He I* triplet is populated by recombination from He II and thus provides a lower limit on the He II column density and, by extension, that of H I. He II λ1640 absorption ($n = 2 \rightarrow 3$) arises only very close to an ionizing source, at a distance which can be determined if He I* absorption is also detected.
- 'redshifted-trough' absorbers which may be due to absorption of an extended continuum source by a rotation-dominated disk wind; the three existing examples are all very faint.
- very high velocity troughs ($\geq 25,000\,\mathrm{km\,s^{-1}}$) where C IV absorption covers the Si IV emission line (e.g.). It is known that 6,000 $\mathrm{km\,s^{-1}}$ outflows are located outside the BLR because their N V absorption covers the quasar's Lyα emission, but it is not known if higher-velocity outflows are also located outside the BLR. If so, and if the column densities are large enough, there must be a non-radiative contribution to the acceleration (Hamann et al. 2002).
- systems with excited state C II* and Si II* absorption, which places a lower limit on the density of $10^{2-4}\,\mathrm{cm^{-3}}$ when seen; assuming gas in photoionization equilibrium with the quasar, the distance of the absorber can be determined, modulo the possible presence of X-ray shielding gas (Hutsemékers, Hall & Brinkmann 2003).
- outflows with evidence for dust, via detection of Zn II but not Cr II absorption (chromium is easily depleted onto dust, while zinc is not). We have not yet found such a system, but the tendency for BAL quasars to be redder than non-BAL quasars suggests they exist.

Absorption System Variability: About 40% of BAL troughs show detectable (≥10%) variations in their strengths on timescales of a few years (Barlow 1994). The shortest timescales observed for variability in the strengths of intrinsic absorption troughs to date are ≤54 rest-frame days in a BAL quasar (Hall et al. 2002) and ≤102 rest-frame days in a narrow absorption system (Narayanan et al. 2003). Using existing repeat spectra, the SDSS is capable of constraining the frequency of such BAL trough variations on to timescales down to a few rest-frame days. Those are the shortest expected trough variability timescales, and although such rapid variations will be rare, the shortest timescale variability puts the best lower limit on the density (for variability due to a changing ionization equilbrium) or the transverse velocity (for variability due to cloud motion).

Suppose we observe absorption from gas in ionization equilibrium with electron density n_e. Then the minimum rest-frame timescale for variability due to changes in that equilibrium (caused by a delta-function increase in the ionizing luminosity) is the recombination timescale $t_r \simeq (\alpha n_e)^{-1}$. Here α is the recombination rate coefficient to the next lower stage, and we have assumed the observed ion is the dominant ion of that element (Hamann et al. 1997). Values of α are typically a few $\times 10^{-12}$ cm^3 s^{-1}, and for at least Fe III-dominant BAL quasars we know that $n_e \geq 10^{10.5}$ cm^{-3} (Hall & Hutsemekers 2003). Thus, recombination timescales $\leq$100 seconds are possible; however, such rapid responses would be smoothed out by light travel time effects even if a delta-function luminosity increase did occur. Because BAL troughs often exhibit partial covering of the continuum source, they must have sizes comparable to that of the continuum source: $d \simeq 6 \times 10^{15}$ cm (Peterson 1997). Thus, the minimum *observable* rest-frame variability timescale is $\sim d/c$, or $\sim 2\times 10^5$ seconds (55 hours). Observing such rapid variability requires an equally rapid continuum outburst, which is rare. The typical timescale for trough variability at levels detectable in the SDSS spectra will instead be set by the typical ionizing continuum variability timescale, which reaches $\sim$15% RMS at 912 Å at $\Delta t \simeq 4 \times 10^6$ seconds (45 days; Ivezic et al. 2004, in preparation).

Similar miminum timescales are expected for trough variability due to the motion of "clouds" (or density inhomogeneities in a continuous wind) across the line of sight. This variability timescale is $t_v \simeq d/v_{cloud}$ (perhaps a factor of a few lower due to partial covering), which for the same size scale as above yields $t_v \simeq 35$ days for $v_{cloud} = 20{,}000$ km s^{-1}.

Fortuitously, repeat spectroscopic observations of SDSS quasars are taken on observed timescales of days, weeks, months, and years, corresponding to the above expected minimum rest-frame variability timescales. Repeat data is taken for several reasons: mostly for quality control (observed-frame timescales of hours to years), sometimes due to inadequate *average* SNR for the spectroscopic plates (timescales of days to months), occasionally due to multiple targeting opportunities where the spectroscopic plates overlap (timescales of hours to years), and rarely because conditions do not allow photometry and there are no new spectroscopic plates to observe (timescales of days, months or years).

During the process of identifying SDSS quasars with intrinsic absorption, the PI will compile a list of such quasars with repeat spectra (perhaps 10% of the total sample). The significance of differences in such repeat spectra is easily gauged, as the noise properties of SDSS spectra have been very well characterized (Bolton et al. 2003). The uncertainties in the SDSS spectrophotometry can be reduced to ±8% (Vanden Berk et al. 2003), so the limiting factors in detecting significant variability are instead the SNR of individual observations and the continuum and emission-line variability of quasars. The SDSS spectra achieve average SNR$\geq$6/pixel at $i \simeq 18$ by design; some plates and bright quasars will have much higher average SNR, but many observations will only be adequate to detect strong trough variations. Variability is a lesser problem, since we are looking for relative and not absolute changes. Each epoch's spectrum will be normalized by its PCA-reconstructed intrinsic spectrum. Observations separated by a week or less can be used to simultaneously determine the repeatability of PCA reconstructions and to flag outliers which may be potential cases of rapid trough variability. If no significant variability is detected on short timescales, the spectra can be coadded for comparison with later epochs.

Given the large size of the SDSS, the possibility exists of detecting rare cases of trough variability at the shortest plausible timescales ($\sim$2 days). But the real power of the SDSS will lie in its several hundred measurements of trough variability (even if mostly upper limits) on rest-frame timescales of weeks, months, and even years, corresponding to densities of 10^4 to $\geq 10^6$ cm^{-3} for ionization variability, or cloud velocities of 10^3 to $>10^5$ km s^{-1} for cloud motion variability. Just as SDSS observations of quasar continuum variability present challenges to accretion theory and quasar models (Vanden Berk et al. 2003), SDSS limits on, and observations of, intrinsic absorption variability as a function of time will provide constraints that must be met by models of quasar outflows.

Summary

The reseach program outlined above is ambitious, but well suited to be the PI's dominant (0.75 FTE) research focus for the next two years. It will consist of implementing Spectral PCA to model the unabsorbed continuum of quasars with intrinsic absorption, and optimizing automated measurements of the AI (and BI, for comparison with previous work), equivalent widths, and other parameters of quasars and their absorption systems deemed useful to advancing the understanding of quasar outflows. It will provide an atlas of intrinsic absorption in ∼3800 SDSS quasars, released in two phases, plus ∼1900 more when the SDSS survey spectroscopy is completed. An estimated ∼75% will come from the subset of homogeneously targeted quasars, which will be used for detailed studies of the correlations of absorption system properties with each other and with other quasar properties. These measurements will be compared to the predictions of theoretical outflow models to refine the models. This project will also provide a large sample of BAL quasars, mostly luminous ones, whose properties make them worthwhile, well-suited targets for high-resolution spectroscopy and multi-wavelength follow-up. Once conference per year will be attended to disseminate and publicize the results of the project. The data, fits and measurements will all be made publicly available, as discussed in the next section.

Broader Impacts

The NSF "expects PIs to share with other researchers ... the data ... and other supporting materials gathered in the course of the work" as part of its broader impacts criterion. The SDSS is making its photometric and spectroscopic data public in a series of data releases (#2: early 2004; #3: late 2004; #4: mid-2005; and #5, with the full 8800 $\deg^2$ of imaging, in mid-2006). To encourage the broad impact of this project and to add value to the SDSS dataset, all the measurements of various properties of intrinsically absorbed quasars compiled during this project will be made publicly available to the entire community in a timely fashion after each SDSS data release. The PI and his collaborators have made similar data from past studies public: spectra of all unusual BAL quasars in Hall et al. (2002), along with prototype IRAF and SM code for calculating *BI* and *AI* values, are available at http://archive.stsci.edu/sdss/quasarBALs/, and composite BAL quasar spectra from Reichard et al. (2003a) are available at http://www.sdss.org/dr1/products/value_added/. *[These and other URLs in this document are understood not to be required reading for reviewers; nonetheless, they have been provided to allow verification of the PI's statements.]*

This project will thus provide an added-value catalog of intrinsically absorbed quasars. Additional studies could be done using the cataloged properties alone. Also, the catalog could be used for identification of sources detected at other wavelengths. Since $\sim 20^{+15}_{-10}\%$ of *all* IRAS-selected quasars are LoBALs (Weymann et al. 1991; Low et al. 1989; Boroson & Meyers 1992), compared to $\simeq$2% among SDSS quasars, and since we now know BAL quasars are typically dust-reddened, a large number of LoBAL quasars may be detected with SIRTF. At higher energies, the X-ray faintness of BAL quasars means that targeted X-ray follow-up must focus on the most luminous members of each BAL quasar subclass (LoBAL, FeLoBAL, Fe III-dominant, etc.). A large survey like the SDSS is needed to identify sufficient numbers of such objects for studies *spanning the full observed range of BAL properties.*

While this particular proposal does not involve funding for students, the PI has a consistent track record of research collaborations with graduate and undergraduate students, and expects to continue such collaborations to promote student learning and training.

Most relevant to this proposal, the PI has collaborated on SDSS BAL quasar work with Tim Reichard (Penn State undergraduate and now Johns Hopkins graduate student) and fellow Princeton postdoc Gordon Richards (see attached letter in Supplementary Documents). The PI has just begun collaborating with Jon Trump (Penn State undergraduate), who is continuing and expanding the work of cataloging traditionally defined BAL quasars from the SDSS. The Principal Component Analysis aspect of this proposal will also involve collaboration with Dan Vanden Berk and Ching-Wa Yip at Princeton (see attached letters in Supplementary Documents). The PI is also assisting U. Wyoming undergraduate Justin Schaefer (advisor: Mike Brotherton) in identifying BAL quasars which are also FR II radio sources (only two FR II BAL quasars are currently known), using the public SDSS DR1 data release, and in interpreting X-ray observations of radio-loud BAL quasars. Mr. Schaefer is being supported through successful *Chandra* and *XMM* proposals awarded to the PI (but being administered by co-investigator and budgetary PI Dr. Brotherton at Wyoming).

The PI also worked with Princeton undergraduate Martin Niederste-Ostholt in June 2003, resulting in his coauthorship on the SDSS DR1 Quasar Catalog paper (Schneider et al. 2003), and third authorship on Hall et al. 2004, "A Quasar Without Broad Lyα Emission," to be submitted. Lastly, the PI is currently collaborating with Princeton undergraduate Phil Hopkins (advisor: Michael Strauss) to publish his junior thesis work, which confirms that dust reddening is the primary explanation for red SDSS quasars, and shows that reddening with SMC-like extinction curves dominates the reddening observed toward quasars (Hopkins et al., to be submitted).

Last but not least, the PI will continue contributing to the popular science website Starstuff.org — "Space News from the Astronomers" (http://www.starstuff.org/), where he is currently the third most prolific contributor (albeit a distant third). This website encourages astronomers to submit a popular science article on every scientific paper they submit. The PI will maintain that submission rate for every paper of his related to quasar research in the SDSS. Some submissions will be to other astronomy popular science article venues such as Mercury, the Journal of the Royal Astronomy Society of Canada, and commercial magazines such as Astronomy and Sky & Telescope.

Results from Prior NSF Support:

While the PI himself has not been previously directly supported by the NSF, the PI and collaborator Dr. Gordon Richards were Co-PIs on NSF proposal AST-0330649: "A Conference on Active Galactic Nuclei Physics with the Sloan Digital Sky Survey - July 27-30 2003" (http://www.astro.princeton.edu/∼gtr/sdssagn2003/). The award was $6,000 for the period May 15, 2003 – April 30, 2004, to support the attendance of postdocs and graduate & undergraduate students actively working in the field.

The conference was held as scheduled, with 113 participants from the US, UK, Germany, Australia, and Israel, including 34 students and 28 postdocs. As organizers, we felt the meeting ran quite smoothly and was scientifically very interesting and productive. The feedback from meeting attendees has been very positive (http://www.astro.puc.cl/∼phall/kudos.txt).

The conference proceedings, with over 100 contributions, will be submitted within a month for publication in the ASP conference series; many have already appeared as preprints on astro-ph. A short conference summary article is also in preparation for PASP.