NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: September 30, 2002 **Category:** Active Galaxies

Redshifted Troughs in Broad Absorption Line Quasars: Testing the Rotating Disk Wind Model

PI: Patrick Hall **Status:** P **Affil.:** Princeton University
Princeton University Observatory, Peyton Hall, Ivy Lane, Princeton, NJ 08544-1001 USA
Email: pathall@astro.princeton.edu Phone: 609-258-3801 FAX: 609-258-1020

CoI: Damien Hutsemekers **Status:** P **Affil.:** University of Liege, Belgium

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
The Sloan Digital Sky Survey has discovered three Low-Ionization Broad Absorption Line Quasars with absorption troughs extending redward of the quasar's host galaxy redshift. These troughs could arise from a rotation-dominated disk wind illuminated by an extended continuum source, or from absorbing clouds randomly orbiting the quasar. These models have very different implications: disk winds mean that LoBAL quasars are just normal quasars seen at certain orientations, but randomly orbiting clouds imply that LoBAL quasars are a distinct population of young quasars surrounded by gas and dust. We propose HIRES spectroscopy of one of these unique objects to perform one of the few tests which can discriminate between these models. Each model makes distinctly different predictions for the trough shapes at high resolution in these objects and for the distances of their BAL outflows from the central ionizing source. The latter can be obtained by modeling high-resolution spectra to constrain the physical conditions in the outflow, which has been done for only a handful of BAL quasars to date.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	Keck-I	HIRESb	1	darkest	Feb - Mar	Feb - Apr
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to four lines)*.

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

One in ten quasars is a Broad Absorption Line (BAL) quasar, but how normal and BAL quasars are related is unclear. Most BAL quasars are HiBALs, with outflowing absorption seen only in high ionization lines like C IV, but 1 in 7 is a LoBAL with low-ionization absorption as well (e.g., Mg II). At one end of the range of BAL quasar models, these fractions represent the fraction of sky around every quasar covered by that type of BAL outflow; at the other, the fraction of all quasars surrounded by that type of outflow. Since BAL outflows have mass loss rates comparable to quasar accretion rates and may be present around every quasar for at least part of its lifetime, determining the correct model(s) for BAL quasars will improve our understanding of all quasars.

The main argument against BAL outflows completely surrounding quasars is that the absorption and emission EWs should be the same in that case (Hamann et al. 1993), whereas the absorption is often much stronger. But line photons can be preferentially destroyed by dust, and BAL quasars are redder than normal quasars (e.g., Becker et al. 2000), probably due to dust. Some LoBAL quasars do show every sign of being recently (re)fueled quasars seen as they expel a shroud of dust and gas (Voit et al. 1993), but it is unclear if this model can explain the observed lack of acceleration in BAL clouds (Wampler et al. 1995). On the other hand, the orientation model – in which all quasars have BALs along some sightlines – arises naturally from models of accretion disk winds (e.g. Murray et al. 1995), and successfully predicts the very high X-ray column densities of BAL outflows (Green et al. 2001). However, Becker et al. (2000) have shown that radio-selected BAL quasars have a range of radio spectral indices, indicating a range of orientations. Thus the need for tests which can differentiate between these BAL quasar models.

The SDSS (York et al. 2000) has discovered three LoBAL quasars which can discriminate between these models (Hall et al. 2002, 2003). Each of these quasars has *absorption troughs that extend redward of the* **secure** *quasar host galaxy redshift* by $\gtrsim$1000 km s^{-1} (Figs. 1-2). HIRES spectroscopy of these objects can provide two independent tests of BAL quasar models. First, modeling the many absorbing transitions in these objects can constrain the distance of the outflow from the central source in each object (e.g., de Kool et al. 2002) — in explaining these objects, the two leading BAL quasar models predict distances which differ by a factor of ten. Second, different BAL quasar models make different predictions for these objects' absorption trough shapes *at high resolution*:

• If they are due to infalling discrete gas clouds crossing our line of sight, the apparently smooth troughs in the SDSS spectra will break up into many narrow ($\lesssim$15 km s^{-1}) lines.

• If the absorption is from an outflow of discrete clouds distributed with a substantial virial velocity dispersion, then the velocity dispersion is likely isotropic, and the clouds will completely surround the quasar. This has been predicted for some LoBALs from other considerations (Canalizo & Stockton 2001), and would mean that BAL quasars are a distinct, 'young' class of quasars. *In this model the extent of the absorption redward of the systemic redshift would be the same for all troughs.*

• If BALs arise in a wind from a rotating accretion disk, and our line of sight passes through the base of the wind where its velocity is dominated by rotation, and if the continuum source is no more than an order of magnitude smaller than the inner radius of the wind, the wind can have both approaching *and receding* velocities along our line of sight (Fig. 3; Hall et al. 2002). *In this model the extent of the absorption redward of the systemic redshift would be smaller for troughs at bluer wavelengths.* This is because the continuum emission at bluer wavelengths is emitted from smaller radii, which decreases the apparent size of the continuum source. The SDSS spectra have limited UV coverage and insufficient resolution to deblend different transitions and detect variation in the trough extents. Our proposed spectroscopy will suffice: it will reach rest 1670 Å, and for a standard $T(r) \propto r^{-0.75}$ accretion disk, $r_{max}(1670\,\text{Å}) \simeq 0.5 r_{max}(2800\,\text{Å})$. Thus, in this model, these objects' Al II λ1670 troughs should have maximum redshifted velocities only half those of Mg II.

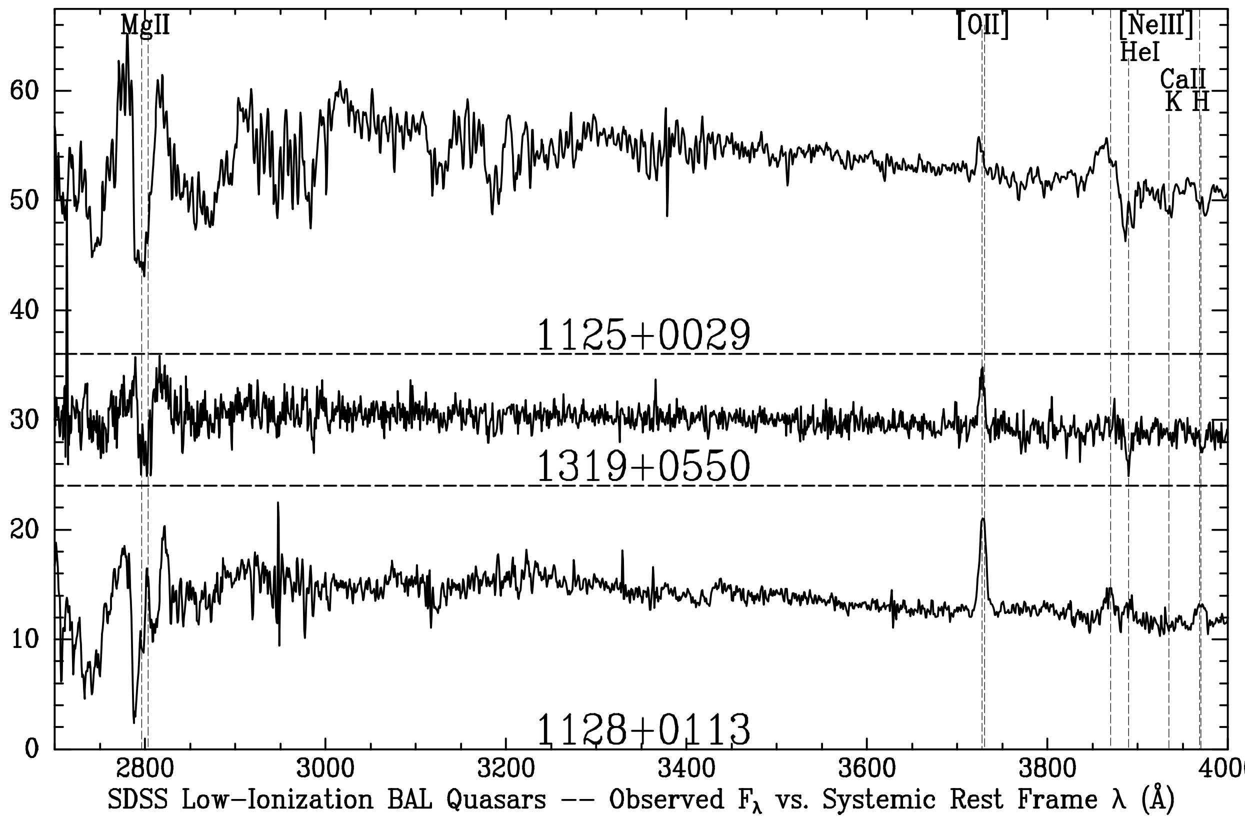

Figure 1: Spectra of our targets from systemic rest-frame 2700-4000 Å. Dashed vertical lines show the wavelengths of Mg II, [O II], He I λ3889, Ca II H&K, [Ne III] $\lambda\lambda$3869,3969 (note the slight emission-line blueshift in 1125+0029). The Mg II absorption redward of the dashed lines shows that the Mg II BAL troughs extend redward of the robust systemic redshifts by $\simeq$750-1700 km s^{-1}, many times the $\sim$150 km s^{-1} resolution. Despite the strong Fe II absorption in the spectra, no Fe II transitions exist which can produce such strong absorption immediately redward of Mg II.

REFERENCES

Arav *et al.* 1999a, ApJ 516, 27
Becker *et al.* 2000, ApJ 538, 72
Canalizo & Stockton 2001, ApJ 555, 719
de Kool *et al.* 2001, ApJ 548, 609
de Kool *et al.* 2002, ApJ 678, 58
Elvis, M. 2000, ApJ, 545, 63
Everett, J. *et al.* 2002, ApJ in press (astro-ph/0201268)
Green, P., *et al.* 2001, ApJ 558, 109
Hamann, F., *et al.* 1993, ApJ 415, 541
Hamann, F., *et al.* 2001, ApJ 550, 142
Hall, P., *et al.* 2002, ApJS, 141, 267 (astro-ph/0203252)
Murray, N., *et al.* 1995, ApJ, 451, 498
Voit, Weymann & Korista 1993, ApJ 413, 95
Wampler, Chugai & Petitjean 1995, ApJ 443, 586

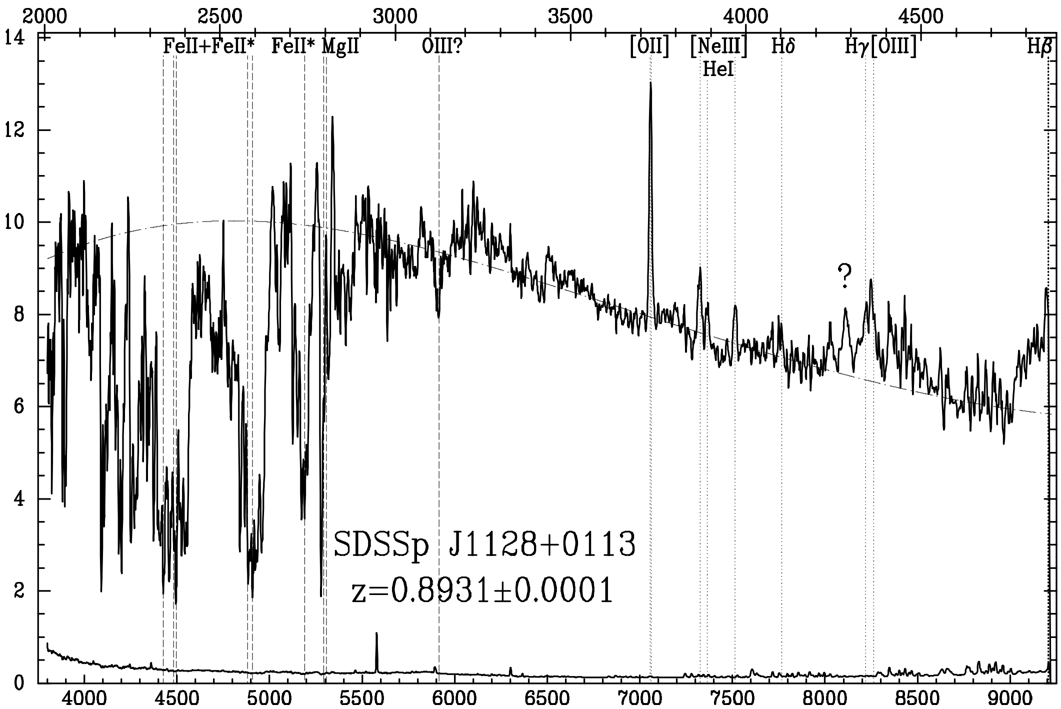

Figure 2: Highest S/N ratio SDSS spectrum of any of our objects (F_λ vs. λ; observed frame on bottom axis, rest frame on top), showing the many absorption troughs present (mostly from Fe II).

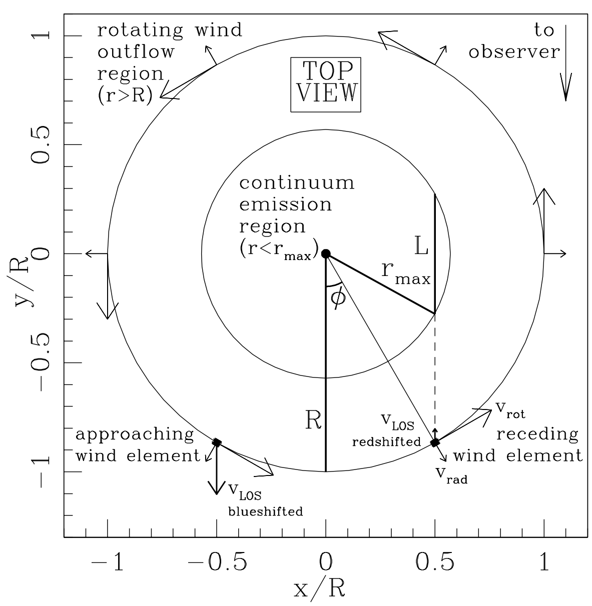

Figure 3: How an extended continuum source and rotating disk wind can give rise to redshifted BAL troughs. In this top view of an accretion disk, the black hole is the dot at (0,0), the y axis is the line of sight to the observer, and the x and z axes are in the plane of the sky. The continuum emission at a given wavelength arises at $r < r_{max}$, and the wind begins at radius R. A wind element at (R, ϕ) will absorb at a line of sight velocity $v_{\rm LOS}$, which will be redshifted if the wind's tangential velocity dominates its radial velocity. The maximum possible redshifted velocity scales as r_{max}/R.

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

High-resolution spectroscopy (R~20,000) is required to model the physical conditions in the BAL outflow in these objects, and to be sure that the redshifted BAL troughs are not merely due to infalling gas clouds crossing our line of sight. We are constrained to use HIRES-b by the redshifts of the three examples of redshifted-trough BAL quasars found to date (among >30,000 SDSS quasars). Given that at least one night is needed for each object (see the Observing Run Details), we request only one night, for the highest-redshift example (SDSS 1319+0550 at z=1.0566). The HIRES observations will enable us to compare the redward extents of troughs in Mg II, Al III, Al II and possibly even C IV, for a firm test of the different models for redshifted BAL troughs.

Because the technique is valuable but not common knowledge, some words are in order on how high-resolution spectra also enable us to constrain the physical conditions in BAL outflows; namely, the electron density n_e, numerous ion densities N_{ion}, and the excitation temperature T_{exc}. (Note that while our objects might be more fairly termed 'mini-BALs' since their outflows might not reach the velocities and widths of traditional BAL quasars, we cannot know for sure without a measurement of C IV, and, in any case, the strength of their excited-state Fe II absorption confirms these outflows as intrinsic to the nuclear regions of these objects, with physical conditions likely to be similar or identical to those in traditional BAL quasars.)

Since most BAL troughs are saturated even though they only partially cover the continuum source (Arav et al. 1999a), constraints on physical conditions can only be derived for rare objects (like ours) with relatively narrow absorption from many different transitions, elements and ions. Most of the absorption lines in these objects are excited-state Fe II transitions from levels up to ~2–3 eV above ground, but we will also cover Fe III at ~1910 Å, Al III $\lambda\lambda$1854,1862 and Al II λ1670. In addition, two of our objects – 1125+0029 and 1319+0550 – show absorption from Mn II, Ti II, excited-state Cr II, and the metastable 2^3S level of He I (populated mainly by recombination of He II, this level sets a lower limit on the column density in He II and therefore H II).

Using the velocity profile of absorption from unblended lines, a model of the entire spectrum can be constructed and fit to the observations, yielding best-fit N_{ion}, T_{exc}, and n_e values in the BAL region (e.g., de Kool *et al.* 2002). Assuming the BAL gas is in photoionization equilibrium with the quasar, the n_e and N_{ion} constraints can be combined with photoionization models to determine the ionization parameter U of the low-ionization BAL gas and its distance from the central continuum source. This distance can be compared with the expected distance for the model that best fits the redward-of-systemic absorption troughs, for an independent check on the validity of that best-fit model. For a disk wind, we expect a distance $\gtrsim 3\times10^{16}$ cm; for a virialized population of clouds, $\gtrsim 5\times10^{17}$ cm (Hall et al. 2002). Either way, such distance measurements are also valuable because they have been made for only 3 other BAL quasars (Hamann *et al.* 2001, de Kool *et al.* 2001, 2002; Everett *et al.* 2002). In two cases the distances are 1-4 parsecs, but the Hamann result on the 'mini-BAL' in 3C 191 is a remarkable 28 kpc! Even if it is just left over from an earlier BAL phase, it is difficult to understand how the gas could remain confined or collimated at such large distances. More BAL region distances from their continuum sources need to be measured to address the issue.

Use of Other Facilities *Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program.*

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

- **Hall** et al.: 4 CNTAC nights 2002B (Jan. 2003) for rest-frame optical survey of $1<z<3$ galaxies
- **Hall**: CTIO1.5m: 12 CNTAC nights 2001AB for 2MASS-selected AGN candidate spectroscopy; selection 65% efficient; paper on serendipitous flaring L dwarf published; AGN paper submitted
- **Hall**, Barrientos, Gladders, Yee, De Robertis: CTIO4m+OSIRIS 2 CNTAC nights 2001A, and KPNO4m+SQIID 4 nights 2002B, for near-IR imaging followup of candidate brown dwarfs & $z>5.5$ quasars from Red-Sequence Cluster Survey; deeper IR followup of 5 potential quasar candidates has ruled them out; many L and T dwarf candidates found, including a candidate L4-L5 10,000-AU binary; 3 good nights of SQIID data being reduced; program continuing at CFHT and Magellan
- **Hall**, Green, Kennefick, Osmer, Smith: 1 night Mar. 1999 w/CTIO4m+HYDRA for Big Faint Quasar Survey spectroscopy; 1 project & 1 backup Deep Multicolor Survey field observed; key targets missed due to instrument software errors; data reduced, results now in online DMS database
- Barrientos, Yee, Gladders, Ellingson, **Hall**, Infante, Kodama: CTIO4m+MOSAIC: 16 CNTAC+NOAO nights 1999B - 2001B for southern Red-Sequence Cluster Survey imaging; 45 deg^2 imaged; first results paper about to be submitted; first catalog paper in preparation
- Kennefick, Falco, Green, **Hall**, Osmer, Smith, Monier, Conti; 8 nights Fall 1999 - Fall 2000 for longslit spectra of candidate z>5 quasars & gravitational lenses from a 40 deg^2 BVIZ survey; two z$\sim$4.75 quasars found despite typically poor seeing & weather; AJ paper in press (astro-ph/0209055)

Observing Run Details for Run 1: Keck-I/HIRESb

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

We will observe one of the three SDSS BAL quasars with redshifted absorption troughs. The highest-redshift object of the three is slightly fainter than the others (Δg=0.2 mags), but the efficiency of HIRES is dropping steeply at the UV wavelengths we need to observe. When that is taken into account, this object – SDSS 1319+0550 at $z = 1.0566$, with $g = 19.9$ – is the best target.

The strong BAL troughs we want to observe are Al II 1670 (observed 3434Å), Al III 1860 (3825Å), and Mg II 2800 (5760Å). This will require two settings with the HIRES-b, one covering 3000-4480Å and the other 4480-5980Å but with gaps. We have verified, using the HIRES-b echelle simulator, that the gaps will not affect coverage of the full MgII trough.

Modeling the physical conditions in the BAL outflow requires a S/N ratio $\gtrsim$15 at a resolution $R\sim$20,000 (Arav et al. 1999a, Fig. 1). To achieve that resolution we can use a $1''$ slit and bin by 2 pixels in the dispersion direction, which also reduces the effects of read noise on the S/N. To calculate exposure times we used the HIRES-r S/N simulator and corrected for the difference in efficiencies between HIRES-r and HIRES-b using the efficiency curves available on the HIRES web site.

We require one night. With 2 hours' exposure at high airmass using the 4480-5980Å setting we will reach S/N=16 at Mg II (all S/N are given per resolution element). With 6 hours' exposure at low airmass using the 3000-4480Å setting we will reach S/N=19.5 at Al III and S/N=8.5 at Al II. This will be sufficient for our purposes, since most of the Fe II absorption complexes useful for constraining the physical conditions in the BAL outflow lie between Al III and Mg II, and the critical measurement at Al II is the redward extent of its absorption trough. We note that our coverage will reach C IV at 3188Å observed, but the S/N at that wavelength may not be sufficient for any analysis.

Instrument Configuration

Filters:	Slit: 1.0 arcsec	Fiber cable:
Grating/grism:	Multislit: no	Corrector:
Order:	$\lambda_{\rm start}$:	Collimator:
Cross disperser: Blue	$\lambda_{\rm end}$:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 11 to 13

Dec. range of principal targets (degrees): +00 to +06

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v2.7.