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LENS-AIDED MULTI-ANGLE SPECTROSCOPY (LAMAS) REVEALS SMALL-SCALE OUTFLOW STRUCTURE IN QUASARS

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ABSTRACT

Spectral differences between lensed quasar image components are common. Since lensing is intrinsically achromatic, these differences are typically explained as the effect of either microlensing, or as light path time delays sampling intrinsic quasar spectral variability. Here we advance a novel third hypothesis: some spectral differences are due to small line-of-sight differences through quasar disk wind outflows. In particular, we propose that variable spectral differences seen only in component A of the widest separation lens SDSS J1004+4112 are due to differential absorption along the sightlines. The absorber properties required by this hypothesis are akin to known broad absorption line (BAL) outflows but must have a broader, smoother velocity profile. We interpret the observed C IV emission line variability as further evidence for spatial fine structure transverse to the line of sight. Since outflows are likely to be rotating, such absorber fine structure can consistently explain some of the UV and X-ray variability seen in AGN. The implications are many: (1) Spectroscopic differences in other lensed objects may be due to this "lens-aided multi-angle spectroscopy" (LAMAS). (2) Outflows have fine structure on size scales of arcsec as seen from the nucleus. (3) Assuming either broad absorption line region sizes proposed in recent wind models, or typically assumed continuum emission region sizes, LAMAS and/or variability provide broadly consistent absorber sizescale estimates of $\sim 10^{15}$ cm. (4) Very broad smooth absorption may be ubiquitous in quasar spectra, even when no obvious troughs are seen.

Subject headings: quasars: absorption – gravitational lensing – quasars: individual (SDSS J1004+4112) – quasars: absorption lines

1. INTRODUCTION

1.1. *Quasar Outflows*

Evidence is accumulating that outflows occur wherever there is accretion. In active galactic nuclei (AGN) the outflows from supermassive black holes (SMBH) are highly ionized, so their signatures appear mostly in rest-frame ultraviolet (UV) and X-ray spectra. From spectroscopy of Seyfert nuclei, at least half show narrow absorption lines (NALs) of highly ionized species in outflows of $\sim$1000 km s^{-1} . From X-ray studies, warm absorber features are present again in about half of quasar X-ray spectra (Piconcelli et al. 2005), and many such features are seen in outflow (Crenshaw et al. 2003a).

More massive, accelerating outflows create broad absorption lines (BALs), whose P-Cygni profiles span velocities to $\sim 0.3c$ and are visible in the spectra of $15-20\%$ of optically-selected quasars (Hewett & Foltz 2003; Reichard et al. 2003) or more in unbiased samples (Chartas 2000). These outflows may exist in all quasars, subtending a solid angle covering fraction at least as large as their detection fraction.

Studies of powerful mass outflows in quasars are rapidly reshaping our understanding of physics near the supermassive black hole. Sightlines that pierce the absorbers yield information on the velocity and plasma state of the gas that is impossible to obtain from emission lines, most likely because the latter are formed by compounded emission from much larger ensembles of clouds in a wide variety of physical states (Baldwin et al. 1995). These broad line-emitting clouds lie at distances of $10^{15}-10^{18}$ cm from the SMBH, spanning a range of densities $n_e \sim 10^8 - 10^{12}\,\mathrm{cm}^{-3}$ and covering $\geq$10% of the ionizing source. Recent models (e.g., Elvis 2000) hold that the absorbing and emitting clouds are not only cospatial but quite possibly identical, making knowledge of absorber properties even more important to our understanding of AGN physics.

For outflows, equatorial disk wind models (e.g., Murray & Chiang 1997; Elvis 2000) are currently favored, although proponents of polar winds exist (Punsly & Lipari 2005; Hartnoll & Blackman 2001). It has often been suggested that outflows may contain a substantial kinetic luminosity (though see Blustin et al. 2005), and impart significant mass and energy into the interstellar (ISM) of the host galaxy and even into the surrounding intergalactic medium (IGM; Roychowdhury & Nath 2002).

A great deal more information about the structure and dynamics of the outflowing absorber could be gleaned if some information about their size scales were available. However, the $\sim$parsec scale emitting/absorbing regions near supermassive black holes (SMBHs) will remain spatially unresolved for the foreseeable future (milliarcsec at $z\sim 0.01$). If the dynamics of absorbers were known (e.g., Keplerian orbits in the SMBH potential), then spectroscopic variability information might also lead to absorber size scales, *viz.* $a_V \sim v_{trans}\Delta t$. Unfortunately, the absorber dynamics are poorly constrained, and multi-epoch spectroscopy is difficult to arrange and therefore rare. Gravitational lensing can help.

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1.2. *Spectral Differences Between Lensed Images*

Because gravitational lensing is intrinsically achromatic, spectral similarity is an early criterion to consider close quasar images as lens candidates. Redshifts, as well as emission and absorption line profiles must be similar. However, significant spectral differences have been noted in *bona fide* lensed quasars (e.g., HE 2149-2745; Burud et al. 2002a, SBS 1520+530; Burud et al. 2002b; Oguri et al. 2005) with clearly identified lensing masses and some with time delays (making the lens interpretation irrefutable). Significant differences in absorber properties between image components have been documented in optical/UV spectra of BALQSO lenses (e.g., APM0829+5255; Lewis et al. 2002, H1413+117; Angonin et al. 1990). SDSS J1004+4112 could represent a more extreme example of this phenomenon due to its wider-angle separation, and/or to fortuitous snapshots of unveiled phases.

One traditional explanation of such spectral differences is microlensing, which preferentially magnifies parts of one image, enhancing spectral components that originate from smaller emitting regions (about the size of the Einstein radius of a star) at the source. Another possible explanation is intrinsic quasar spectral variability, combined with lensing time delays.

The recent discovery of the gravitationally lensed quadruple-image $z = 1.734$ quasar SDSS J1004+4112 (Inada et al. 2003; Oguri et al. 2004) is exciting because of its record-setting separation (maximum of $14.6''$ between images). A z=0.68 cluster centered among the four lensed images is confirmed as the massive lens. More recently, deep ACS and NICMOS images of SDSS J1004+4112 from *Hubble Space Telescope* (*HST*) (Inada et al. 2005) have now revealed clear arcs, sheared images of the quasar host galaxy, and a probable 5th quasar image, all of which substantially constrain the plethora of viable lens models. Here we discuss primarily the 4 brighter image components $A - D$ with existing spectroscopy.

In addition, there are intriguing differences between the spectra of the 4 quasar images. Both microlensing and variability have been posited to explain the spectral differences, yet both explanations have serious problems.

Here we advance a novel third hypothesis that has only been mentioned in passing (e.g., Lewis & Belle 1998; Oguri et al. 2004) - line-of-sight differences through quasar outflows. We propose that SDSS J1004+4112 offers a revealing multi-angle view of quasar winds originating near the nucleus, where absorption can change on small angular and time scales. While there are challenges also for this new hypothesis, several of its predictions are immediately testable. Given the wide ramifications for AGN physics, it is well worth considering.

In the next section, we briefly review the spectral evidence, and troubles with the more traditional explanations. Then we examine the prospects and predictions of our own hypothesis.

2. SPECTRA OF SDSS J1004+4112

2.1. *Description*

In SDSS J1004+4112, the blue emission line wings of the brightest image A are enhanced relative to the spectra of image components B, C and D. The ratios of component spectra reproduced in Figure 1a from Oguri et al. (2004) reveal that the differences are larger for Ly$\alpha\lambda$1216/N Vλ1240, SiIV+OIV]λ1400 and C IVλ1549 lines than for the lower ionization lines of CIII]λ1909 and MgIIλ2800. There are subtle differences between the ratio spectra A/B, A/C, and A/D, but the general features are similar; the spectrum of A is the most divergent, with strong blue wings to the emission lines. [1] The continuum flux ratios are approximately constant from 3000 – 8000Å. [2]

Figure 1b, direct from from Richards et al. (2004), focuses on multi-epoch spectra of the C IV emission line in components A and B. The 7 spectra shown span observed-frame time delays of 322 days. An enhancement of the blue wing of C IV in A was seen in the first (03 May 2003) spectrum which lasted at least 28d (since it is seen on 31 May), and then faded (since it was not there 21 Nov). Not shown in the figure are later epochs when the enhancement *reappeared* — seen in a spectrum of 26 Mar 2004, and again 10 and 19 April 2004 (Richards, Johnston, & Hennawi 2004; Wisotzki et al. 2004).

2.2. *The Microlensing Hypothesis*

Could the blue wing enhancement in A be due to microlensing? Microlensing of the broad emission line region (BELR) can occur if it has structure smaller than the Einstein radius ($\sim 3\times10^{15}$ cm for a $0.1 M_\odot$ star). Several problems plague the microlensing explanation: [1] Microlensing should amplify not just the BELR, but also the hot continuum-emitting region interior to it. While the single star approximation is poor for microlensing at significant optical depth (the situation for multiply imaged quasars), caustic models show a strong general correlation between the magnification of the continuum and of the BLR, and it is extremely rare for the BLR to be magnified but not the continuum (Lewis & Ibata 2004). No amplification of the A continuum was seen (<20%; Richards et al. 2004) and the A and B continuua are effectively identical (Wisotzki et al. 2004). [2] If the microlensing hypothesis is correct, then microlensing does not act on the (smaller) continuum region but somehow acts only on a select region of the BELR, and that this same configuration *recurs*. The reappearance of the same enhancement renders the microlensing explanation particularly unlikely. [3] Strong line profile differences are also seen in the blue wings of the lower ionization lines of CIII] and MgII (Richards et al. 2004). In most BELR models, these come from significantly larger regions than does C IV emission, and should be less susceptible to microlensing. [4] Line asymmetry induced by microlensing is expected for certain kinematic models of the BELR (Abajas et al. 2002), the closest match being for a modified Keplerian BELR with small lens size. The A profile has varied strongly. Similar profile variations would be expected in other lensed systems but have never been

[1] We note that, while not relevant to the present discussion, Oguri et al. (2004) discuss also the variable strengths of narrow intervening e.g., MgII absorbers that can be seen in these spectra.

[2] Not all spectra were taken at the parallactic angle, so the continuum slopes are suspect. However, neither would we expect these parallactic angle effects to conspire to produce flat continuum ratios.

seen.[3]

We note that in the ACS and NICMOS images (Inada et al. 2005), a dim object (G4) is detected within $\sim 1''$ of image A that could host a microlens. However, it is uncertain whether or not the object is a galaxy, and even more so whether it could provide a microlensing optical depth at the position of image A sufficient to explain the observed variations.

2.3. *Variability*

Spectral differences in many lenses are plausibly explained by intrinsic variability combined with time delays, meaning that with 4 images, we are effectively viewing one quasar at 4 epochs. Given the asymmetry $(r_A - r_B)/(r_A + r_B)$ of the A and B images with respect to the lens, the *maximum* delay between them is $\lesssim 30$ days (Oguri et al. 2004). However, B never showed a blue wing bump, although it persisted in A for *at least* a month (Richards et al. 2004). Also, the persistently bluer profiles in A should have appeared within ~30d in B (or disappeared in A depending on which image lags) but have not: the variability has been confined to A. For these reasons, the usual hypothesis of intrinsic variability plus lightpath time delay appears unlikely to be correct. However, the temporal coverage of spectroscopy to date can not entirely rule out intrinsic variability plus time delay (see Richards et al. 2004 for a full discussion).

2.4. *Lens-Aided Multi-Angle Spectroscopy through Absorbing Fine Structure*

Lensing geometry actually provides slightly different sightlines to the lensed object, and the image separation θ is similar to the angular difference between the lines of sight as seen from the quasar nucleus $\Delta\phi$ (Schneider, Ehlers, & Falco 1992). Indeed, Chelouche (2003) recently pointed out the utility of lensed images of BALQSOs for probing absorber structure transverse to the line of sight.

We propose that small angular differences in sightline afforded by lensing (lens-aided multi-angle spectroscopy; LAMAS hereafter) can probe significantly different absorbing columns in quasars. In the case of SDSS J1004+4112, we propose that all 4 image components suffer from absorption from a warm outflowing wind (similar to that proposed by Elvis 2000 and others), and that the spectral differences are due to a line-of-sight to component A that pierces a persistently thinner and patchier part of the absorbing flow. A transient hole or "rend" in the flow along that sightline is responsible for the blue wing C IV enhancement in A.

We note that a surprising Galactic analogy to LAMAS exists in the massive young star η Carinae. There is a dusty axisymmetric bipolar "Homunculus", formed by ejecta from η Car, which creates a hollow reflection nebula. Spatially-resolved *HST* STIS spectra of the Homunculus (Smith et al. 2003), whose 3-dimensional structure is fairly well-modeled, samples reflected light from the star emerging at different stellar latitudes and probing different parts of the outflow. At viewing angles separated on arc sec scales, large differences in the broad ($\sim$1000 km s^{-1}) P Cygni absorption profiles are seen. Outflow structure in a young massive star may well be qualitatively different than in an AGN, but the dense line-driven wind and the strong angular dependence of the absorption are analogous.

First we present evidence that the blue enhancements in SDSS J1004+4112 A could be due to the alleviation of absorption along this sightline. Second, we report on significant variations common in AGN absorbers. Third, we address the geometry – how different lines of sight may probe significantly different absorber properties and what constraints this and variability place on the absorber structure. Fourth, we address some possible objections to our hypothesis.

3. RENDING OF THE VEIL

The ratio spectra shown in Figure 1a are strongly reminiscent of the structure seen in BALQSOs. To illustrate this with typical spectra, we take the the rest-frame non-BAL composite spectrum from the SDSS (Reichard et al. 2003), assumed to be "unabsorbed". Next we generate "part-BAL" spectra by combining that composite with the SDSS high-ionization BAL composite spectrum. The non-BAL spectrum is shown at the top of Figure 2, along with three example part-BAL composite spectra generated by adding 25, 20, and 15% of the SDSS high-ionization BAL composite spectrum. Even though we plot the logarithm to make differences as visible as possible, no clear absorption signature is evident even in the 25% part-BAL spectrum. Then we divided the part-BAL composite by the "unabsorbed" (non-BAL) composite (lower panel of Figure 2). While some features may differ in detail, note the overall similarity to the spectral ratios seen in Figure 1 for SDSS J1004+4112.

The BAL and non-BAL composites have all their features smoothed and broadened by the averaging process. These composite ratio spectra (of a part-BAL to a non-BAL composite) in Figure 2 show strong similarities to the SDSS J1004+4112 image component spectral ratios in Figure 1. This implies that absorption may account for the differences along the sightlines to the different images. Furthermore, there are 2 reasons to think that the absorbing outflows in SDSSJ1004 may be smoother and broader than normally associated with BALs: (1) adding a smooth/broad absorbed spectral component as in Figure 2 (TOP) does not create recognizable absorption signatures, nor are such signatures visible in the BCD spectra. (2) The similarity of the ratio spectra in Figures 1 and 2 suggest that the absorption troughs in the BCD components may also be smoothed and broadened, as are those in the composites. Normal BAL-type absorbers typically show steep trough edges, which are clearly absent in SDSS J1004+4112. While the absorption in the BAL composite is smoothed by averaging many sightlines to different normal BALQSOs, the absorber we hypothesize to exist in SDSS J1004+4112 must be smoothed in velocity for a different reason. We propose that the absorber profile is *intrinsically* smeared broadly in velocity and consequently smooth onset and trailoff, i.e., with a profile more like a shallow bowl than a trough. Because such absorption is easily missed, this may be a higher covering-factor but lower-column counterpart to more typically remarked BAL flows.

We propose that virtually all quasar sightlines penetrate a warm (ionized), relativistically outflowing wind

[3] While SDSS J1004+4112 is uniquely wide, this is irrelevant to microlensing.

which is smooth in velocity space but may be spatially clumped or filamentary. These ionized winds would quite normally sculpt the emission line profiles of all quasars, particularly in the UV. Excess emission in the blue wing flux of resonance lines is not uncommon (Bachev et al. 2004), and is predicted in the models of Murray & Chiang (1997) (see their Fig 7). The latter authors note that "observed profiles are even more antisymmetric than the calculated profiles. Our neglect of scattered line photons may be partially responsible for this. The absorption troughs in BALs provide direct evidence for the existence of such scattered line photons."

In the case of SDSS J1004+4112, our line of sight to A, as influenced by the lensing geometry, probes through part of the absorber whose column density is somewhat less dense, and also more susceptible to the appearance of gaps in the patchy or perhaps filamentary absorber.

As a microlensing effect, similar blue wing enhancements would not be expected in unlensed quasars. However as either a variability or a line-of-sight effect, they should be seen (with as yet unknown frequency) in the general (unlensed) quasar population. We investigated the emission line properties of AGN from the large sample of *HST* FOS line measurements of Kuraszkiewicz et al. (2002, 2004). While their spectral analysis was both careful and uniform, the sample is heterogeneous, and our perusal subjective, so we cannot draw firm conclusions on the fraction of objects with blue asymmetry at this strength. However, we find several examples of C IV lines with asymmetry similar the SDSS J1004+4112 spectrum seen in Figure 1. The spectrum and model fits to PKS J2355-3357 are shown in Figure 3. This suggests that the same phenomenon occurs in other objects along unlensed sightlines as expected. Because we have no multi-epoch spectroscopy of these objects, we do not know whether the phenomenon is typically transitory.

The absorbing structure we propose is not identical to a BAL flow as typically observed: its velocity profile is broader and smoother. This is because no steep trough edges are seen in Figure 1. (Of course, no steep edges are seen in the comparison composite spectrum of Figure 2 either, but this is due to the fact that the SDSS BAL composite is an average of 180 SDSS BALQSOs, whose BAL troughs have a range of detachment velocities and velocity profiles.) Broad smooth outflow velocity profiles are plausible because BALQSOs with unusually wide, smooth absorption have been found. Extreme examples like VPMS J1342+2840 (Meusinger et al. 2005), SDSS J0105-0033 and SDSS J2204+0031 (Hall et al. 2002) lack any evidence for the usual restframe UV emission lines, yet they show relatively blue continua with no obvious dust reddening. The most convincing explanation to date of their spectral features is unusually wide, overlapping low-ionization BAL troughs (loBALs). Since these objects are quite difficult to recognize and classify, they are likely severely under-represented in existing AGN samples. From our crude spectral arithmetic in Figure 2 and from the fact that most quasars do not show X-ray absorption signatures as strong as in BALQSOs, the flow we propose probably has lower overall column than typical BALs. Indeed, there is evidence that the frequency of quasar absorption increases towards lower columns (Reichard et al. 2003), making more plausible a ubiquitous low-column smooth absorber.

The disk wind scenario (Murray & Chiang 1997; Elvis 2000) fits naturally into this picture, since the absorbers are smoothly accelerating outflowing sheets of warm ionized plasma. In the disk wind scenario, radiative acceleration is in the radial direction, but the disk from which the wind arises is rotating at approximately Keplerian speed until the last marginally stable orbit (Murray et al. 1995). Put simply, the outflows are almost certainly rotating, creating helical streamlines. These are thought to be rising off the disk to create a "martini glass" funnel-shaped outflow (Elvis 2000).

We might expect that holes or flow gaps would appear more commonly along the sightline to component A of SDSS J1004+4112 if it is less absorbed generally (see Figure 4). Even after the obvious blue wing bump subsided during later 2003 epochs shown in Figure 1b, the blue/red flux ratios (measured 20Å to either side of C IVλ1549) are $R_A = 1.15$ and $R_A = 0.84$ (both ± 0.05). This supports our hypothesis of persistently lower column along the sightline to the A image component.

3.1. *Variable Absorption*

Time-dependent calculations (Proga et al. 2000) show that disk wind instabilities result in a filamentary substructure to the flow, so we naturally expect column density variations to occur along our sightline, which would more strongly affect the blue line wings. Rotation combined with clumpy outflows predicts absorber variability. This prediction should be borne out in absorbers seen in unlensed quasars.

In the UV, BALs have been seen to vary strongly in QSOs. At least one BALQSO spectroscopic monitoring campaign has been performed (Barlow 1994), which showed BAL variability in 15 of 23 BALQSOs. Significant BAL variability has been reported anecdotally elsewhere (CSO203; Barlow et al. 1992, SDSS 0437-0045; Hall et al. 2002). The BALs in at least one quasar have disappeared completely (Ma 2002). Variations may be due to a combination of factors, including a change in line-of-sight column, covering factor of the absorber, or ionization. Variability is well-documented and quite common in the narrower absorbing systems seen in lower luminosity AGN (Seyferts) such as such as NGC3516 (Koratkar et al. 1996) and NGC4151 (Kraemer et al. 2005) and others, as reviewed by Crenshaw et al. (2003a).

In the highly ionized circumnuclear environment, X-ray spectroscopy is a sensitive probe of column density because metals in virtually any ionization state will absorb X-rays, whereas optical/UV continuum absorption requires the presence of dust. For instance, while the continua of high-ionization BALQSOs are at most only mildly reddened (Reichard et al. 2003), BALQSOs are strongly absorbed in X-rays (Green et al. 2001; Gallagher et al. 2002a). As measured by X-ray spectroscopy, variations in the absorbing column density by factors of a few are quite common in both optical broad and narrow line (Type I and II) AGN. In Seyfert 2 galaxies, 20 – 80% variability in the measured absorbing column is endemic (23 of 24 objects; Risaliti, Elvis, & Nicastro 2002), and is likely due to bulk motion of material across the line-of-sight. Gallagher et al. (2004) found a column variation of 6×10^{22} atoms cm^{-2} in BALQSO PG2112+059 over a ∼3yr timespan. Gallagher et al. (2002b) discovered hard-band variability at the 45% level on a timescale of 20 ksec in the nearby mini-BAL QSO Mkn 231. More dramatic changes are also seen. UGC 4203 underwent a transition in its X-ray spectrum from Compton-thick to thin (Guainazzi et al. 2002), and NGC 3227 did the opposite (Lamer et al. 2003). The authors suggested the transition could be absorbing clouds or streams crossing our line-of-sight. An X-ray "unveiling event" was noted in NGC4388 by (Elvis et al. 2004), corresponding to a decrease in column of a factor of 100 in just 4 hours. Variability so rapid puts the NGC4388 absorber at a few $100\,R_S$ ($\sim 3\times10^{15}$ cm for $M_{BH}=10^8\,M_\odot$), similar to the broad emission line region or smaller.

Absorber variability is clearly common if not endemic even in the general (unlensed) AGN population. Such variability should provide a geometric constraint a_V on the absorber sizescale from $\Delta\,t$ that is complementary to the LAMAS sizescale a_L from θ.

4. GEOMETRY

From the LAMAS perspective, the different absorber properties of the two sightlines constrain the lateral sizescale a of the absorber as simply as $a_L \sim R_a\theta$, where R_a is the absorber distance and θ is the observed image splitting wherein a signifcant absorbing column change is seen. The difficulty here is twofold. First, there are at best only loose constraints on location of the broad absorption line region (BALR): debate over R_a still spans 5 orders of magnitude from 0.01 to 1000 pc (Elvis 2000; deKool et al. 2001; Everett et al. 2002)! Second, the smooth, broad absorbing flow we propose may span a different spatial regime than the dense flows responsible for BALs (the BALR).

We first assume that $R_a \sim R_{BELR}$. From reverberation mapping (Peterson 1997), the size of the high-ionization (C IV) BELR in NGC 5548 is R ∼10 lt-day, or $\sim 10^{16}$ cm. However, in higher luminosity objects like SDSS J1004+4112, reverberation time lags can easily reach 100 lt-day and more. (The BELR size scales as $R_{BELR} \propto 0.01\,L_{44}^{1/2}$pc from the central continuum source, where L_{44} is the $0.1-1\mu$m luminosity in units of 10^{44}erg s^{-1} (Netzer & Peterson 1997; Peterson et al. 2004).) If the absorber is at a distance similar to the BELR (assuming 100 lt-days), then the A/B spectral differences seen in SDSS J1004+4112 across $\theta = 3.7''$ imply that cloud/stream columns can change significantly on size-scales of $\sim 5\times10^{12}$ cm or $\leq$ 1A.U. transverse to the line-of-sight.

If we assume that the LAMAS and variability both probe the same absorber size scale, how do these sizes compare? Suppose the flow to be in quasi-Keplerian rotation at $\sim 10^4$ km s^{-1} (the median FWHM of broad component of C IV emission; Kuraszkiewicz et al. 2004). The observed variability timescale of the C IV blue wing thus potentially presents a *separate* ($\Delta\phi$) size constraint complementary to that of LAMAS (θ) discussed above: the blue wing bump disappearing from A in < 43days (in the rest frame; Richards et al. 2004) constrains the transverse size of a rend or flow gap to $a_V \lesssim 4\times10^{15}$cm (∼270 AU). If we again assume transverse cloud motion created the variable line profile, but instead of postulating a privileged sightline to A we make the (unlikely) assumption that with adequate monitoring, the same change *could* have been seen to occur in components $B-D$, then the lensing delay timescale is a more appropriate comparison. Since most lensing models for SDSS J1004+4112 in Oguri et al. (2004) predict a time delay $\lesssim 30$ days, the result for a_V is therefore similar. Either way, a_V is inconsistent with (1000×) the LAMAS sizescale a_L based on $R_a \sim R_{BELR}$ above.

Using a single-phase wind to model the outflows from FIRST J104459.6+365605, deKool et al. (2001) found the low-ionization BAL region must be at R_a ∼700 pc. In this case, the lateral absorber size implied by LAMAS is $a_L \sim 4\times10^{16}$ cm, which is 10× larger than the variability sizescale. However, the deKool et al. (2001) sizescale is vary hard to reconcile with partial covering seen in BALs. Everett et al. (2002) instead used a multi-phase outflow model that successfully reproduced the many absorption features (having different ionization parameters but similar velocity structure) by placing the absorber at ∼ 4pc from the central source. Using this value for R_a, LAMAS yields ($a_L \sim 4\times10^{14}$cm or 30 AU), about 10× *smaller* than the variability estimate.

So if our LAMAS proposal holds true, the absorber distance is inconsistent with most BELR distance estimates of $\sim 10^{16}$ cm, but falls somewhere between the best recent estimates of the absorber distance R_a for BALs of $5 \leq R_a \leq 700$ pc.

As an independent estimate, we consider that from an absorbed sightline, the covering fraction of the absorber must be reasonably large (between 0.1 and 1) for a small change in viewing angle to significantly affect the absorption profile. Put differently, the size of the continuum region as seen from the absorber distance must not be too large, otherwise a small change in viewing angle would not detectably alter the absorption profile. For SDSS J1004+4112 (with its 3.7″ splitting), this implies that $R_a \geq 50000\,a_C$, where a_C is the projected UV continuum emitting region size. Because a_C is thought to be about $\sim 30-50\,R_S$, for an accreting supermassive black hole of $10^8\,M_\odot$ we expect that $a_C \sim 10^{15}$, yielding $R_a \geq 5\times10^{19}$cm or ≥10 pc. While independent from the above geometrical arguments, this covering fraction argument under the LAMAS hypothesis yields a similar plausible absorber sizescale (10^{15} cm). Note that if spectra were to show the absorptionn of both continuum and substantial BELR flux, then the absorber distance implied by this latter argument would be quite large ($\gtrsim$1 kpc).

5. OBJECTIONS

Several objections to LAMAS leap to mind.

How could it be that the absorption changes on arcsecond sightline scales but is identical in components $B-D$, some of which are more widely separated from each other than from A? Our proposal is that our sightline to A is unique in this system, perhaps skirting the edge of a larger-scale structure like a disk wind, as illustrated crudely in Figure 4. However, there is no reason in the LAMAS picture that only one component could show a distinct absorption profile. Spectroscopic monitoring of this and other lenses may well identify such cases, which would help confirm the model. Our absorption interpretation would be most sensitively verified by simultaneous UV and X-ray monitoring of spatially-resolved image components in this and other lenses.

SDSS J1004+4112 is not a BALQSO. Most or possibly *all* QSOs contain BAL-type outflows (Hamann & Ferland 1993). But the classic deep BAL troughs are observed only for sightlines traversing dense BAL streams (Ogle 1999), whereas lower-column parts of the flow cover more solid angle and may affect the emission lines less spectacularly in *most* QSOs (Green 1998). Reichard et al. (2003) noted that the fraction of quasars with BALs increases strongly towards lower BALnicity, so that "the fraction of quasars with intrinsic outflows may be significantly underestimated." Broader, smoother outflows such as proposed here be even harder to detect, but could be ubiquitous.

If such smooth, broad outflows are ubiquitous, what special conditions yield more typical BALs, which are detached blueward of the emission line peak velocity? Since their measured X-ray column densities are highest of all types of QSOs, the densest part of the wind is probed by BAL-type outflows. In a disk wind structure alà Elvis (2000), the arch of the BAL wind (as it moves from predominantly vertical to radial velocity) means that it is already accelerated when it first crosses our sightline (Figure 4). This need not be true for the WHIM that transports the BAL material. The WHIM can pervade a much larger opening angle, and be accelerated from a lower velocity.

If smooth, broad outflows are ubiquitous, why aren't most quasars absorbed by columns as large as $\sim 10^{22}$ in the X-ray regime? X-ray spectral fitting to absorption *features* in bright optical- and radio-selected quasars typically yields measured columns of $\sim 10^{21}$ (Reeves & Turner 2000). However, very broad features from warm ionized gas would not be easily detected, just as they are unrecognized in the majority of UV spectra. In fact, for Seyfert 1s and radio-quiet quasars lacking obvious strong absorption signatures in the UV and X-ray regimes, there is a ubiquitous and poorly explained broad soft spectral excess below about 2 keV. Gierliński & Done (2004) and Sobolewska & Done (2005) have interpreted the soft excess as an artifact of previously unrecognized, relativistically smeared, partially ionized absorption; strong very broad O VII, O VIII, and Fe absorption features at 0.7 – 0.9 keV can lead to an apparent upward curvature below these energies, mimicking soft excess emission. Whether such flows are related is still unclear. Their proposed X-ray absorber velocities ($v/c \sim 0.2$) greatly exceed what we see in the UV spectra of SDSSJ1004 ($v/c \sim 0.04$), but the absorbing zones may be disjoint (Crenshaw et al. 2003b) or stratified (Steenbrugge et al. 2005), or the velocity range may vary between objects.

Some significant details of the part-BAL composite spectra in Figure 2 differ from those of SDSS J1004+4112. Figure 2 is meant to be illustrative only, because there are several reasons why those spectra differ in some of the details: 1) The BAL composites are rather heavily smoothed (by dint of averaging many BALs with different velocity profiles). Weaker features are thereby blended away, and then further diluted by the weighting in the part-BAL composite. 2) Details of the composites depend on their method of construction: how the mean is weighted, in what rest wavelength region the contributing spectra are normalized, the dereddening algorithm, and how the quasars' systemic velocity is defined for deredshifting. Furthermore, the SDSS sample selection and spectroscopy means that QSOs contributing to the composite have varying luminosity, redshift, and intrinsic reddening as a function of rest wavelength (Willott 2005). 3) The SDSS composites match SDSSJ1004 in neither luminosity nor redshift, so that related emission line differences are expected (e.g., the Baldwin effect Yip et al. 2004; Green 1996) in CIII] and HeII. 4) True BALQSOs typically show other differences in emission line profiles and strengths relative to non-BALQSOs that are possibly related to an enhanced accretion rate (e.g., Boroson 2002). 5) The LAMAS outflow may sample different regions than typical BAL flows, perhaps with different launch point and/or acceleration profile. Assuming a (e.g., biconical) disk-wind outflow model, our sightline to SDSS J1004+4112 *A* may be somewhat farther from the denser part of the outflow, especially given the claim of repeated 'rending' of the flow. In this part of the outflow (e.g., the lower column warm highly ionized medium - the 'WHIM') the pressure/ionization balance may be different than in a typical BAL flow. Given so many caveats, the accordance between the BAL composites and Figure 1 seems rather remarkable. And certainly no plausible, testable combination of emission line production and microlensing theory is yet available that can reproduce the SDSS J1004+4112 spectra as well.

6. CAVEATS

Whether due to different effective orientations (caused by lensing-induced sightline difference) or to time variability, differential absorption by itself may not be able to produce three key features seen in the spectral differences between components. First is the apparent absorption in CIII]λ1909 and He IIλ1640. Second, the LAMAS model implies that emission lines in most quasars would have an intrinsic blueward asymmetry except for typical broad smooth absorption caused by warm outflowing winds. If true, emission-line profiles *not* subject to resonant absorption (e.g., CIII]λ1909) should retain that asymmetry in the general AGN population. Finally, we discuss the apparent observed change in the red wings of the emission-line profiles (between images and also temporally).

1) The blue wing of the C III] emission profile also appears to be enhanced in image A relative to the other images (see Figure 4 of Richards et al. 2004), but there should be no absorption (and so no differential absorption) detectable from the semi-forbidden C III] transition. However, this spectral difference may still be due to absorption from another species, since BALQSOs can show some spectral signatures there. This is evident for instance in the plots like Fig 10 of Richards et al. (2002), where their BALQSO composites show some significant C III] line strength and profile differences from the non-BAL composite. The trough seen near restframe 1909Å in Richards et al. (2004) Fig 4 is not necessarily from CIII]. FeIII absorption (UV34,UV48) are strong iron lines in the CIII] region (Graham et al. 1996). Such lines have been seen in absorption in BALQSOs e.g., Fig 22 of Hall et al. (2002), though those tend to be in the more rare low-ionization BALQSOs (loBAL QSOs)

only.[4] For unknown reasons, strong Fe II and Fe III *emission* blends are endemic to BALQSOs generally, and correlate with BAL strength (Weymann et al. 1991).[5] So, some differences in iron blend profiles are not unexpected if the *BCD* component spectra are more BALQSO-like.

Also troubling is that the SDSS J1004+4112 ratio spectra appear to show an absorption feature in HeIIλ 1640 which is rare in BALs. Some effect *related to* absorption may be at work here. For instance, for reasons as yet unknown, the He II emission feature in BALs, and in objects with larger CIV blueshifts is weaker and broader in general (c.f. BALQSOs and composite C in Figures 4 and 10 of Richards et al. 2002).

2) In the general AGN population, emission-line profiles that are *not* subject to resonant absorption (e.g., CIII]λ 1909) should retain the blueward asymmetry implied by the differential absorption hypothesis. While this is a cogent objection to the differential absorption hypothesis, it has only weak empirical evidence available to test it because there are very few strong nonresonant emission lines seen in AGN spectra. CIII] is the strongest, and even in the absence of strong iron blends, it is most often heavily blended on the blue side by SiIII]λ 1892 and Al IIIλ 1862 (e.g., Vestergaard & Wilkes 2001). The best resolved example is probably Ark 564 (Leighly & Moore 2004), which indeed shows isolated symmetric CIII] lines at the systemic redshift, which mates poorly with the differential absorption hypothesis. However, this very narrow line Seyfert 1 is hardly representative itself.

3) The observed excess in the red wings of the emission-line ratios in Fig 1a is significant, and nothing similar is seen in Fig 2. At least for CIV, the emission peak is often blueshifted in BALQSOs: features in composite spectra of quasars with larger blueshifts correlate with composites of increasing BAL-type (hi towards loBAL) absorption (Fig.10 in Richards et al. 2002. This works against a hypothesis of differential absorption, because B, C, D as the more absorbed components should show blueshifted, not redshifted emission profiles.

7. IMPLICATIONS AND PREDICTIONS

An appealing aspect of our model is that it is subject to immediate observational tests. X-ray observations of BAL samples (Green et al. 2001; Gallagher et al. 2002a), measure intrinsic absorbing columns of $N_H^{intr} \geq 10^{22}\mathrm{cm}^{-2}$, much higher than naively derived from the (typically saturated) UV BALs. Since we propose that A is seen via a typically less-absorbed sightline, A could show a less absorbed X-ray spectrum, and also larger f_X/f_{opt} relative to components $B-D$. Differential absorption studies of lenses have been difficult in X-rays, due to the close ($\sim 1''$) spacing of lensed images (Morgan 2001; Chartas 2002), but are quite feasible with wide lenses like SDSS J1004+4112. An 80 ksec X-ray observation of SDSS J1004+4112 was performed by Chandra in January 2005. The one caveat to this prediction is that the highly-ionized, high velocity flow proposed may require high S/N X-ray spectra to detect and model correctly (Gierliński & Done 2004).

Since we further propose that A is susceptible to show gaps in the absorber flow, X-ray measurements during a similar UV blue emission line asymmetry event could show substantially lower absorption. A very crude estimate based on Figure 2, and typical BAL columns as measured in the X-rays of $\leq 10^{23}$ (Green et al. 2001) suggests a column change of $\sim 10^{22}$. Alternatively, X-ray spectral fits might also reveal a change in *covering factor* of the absorption.

Wide quasar pairs at similar redshifts are under intense study as possible wide lenses and have been hunted in large surveys like the 2dF (Miller et al. 2004) and SDSS (Inada et al. 2003; Oguri et al. 2005). In a large enough statistical sample of lenses, LAMAS predicts that the degree of spectral difference should correlate with separation angle, and should be independent of proximity to a bright galaxy of high microlensing optical depth. The same can be said for the variability + time delay interpretation, but in that case, adequate spectroscopic monitoring should reveal propagation of spectroscopic features to all image components.

Perhaps the most controversial part of this proposal is its implication that *all* quasar spectra might be self-absorbed at some level by their smoothly outflowing winds, but that this fact has escaped our notice since quasars were discovered some 40 years ago (Schmidt 1963). However, the origin of observed emission line profiles and even the quasi-power-law continuum of quasars remain in general poorly understood. Both their overall similarity and their diversity are difficult to explain (Baldwin et al. 1995). Absorbing winds may be a crucial missing component.

Variable absorption may also be endemic. The salient characteristics of quasar variability seem to be (1) timescales of months to years (2) lower luminosity quasars have larger amplitudes of variability (3) at all redshifts, variability is larger at shorter wavelengths (quasars are bluer when brighter) (4) variability amplitudes increase with redshift, indicating evolution of the quasar population or the variability mechanism (de Vries et al. 2005). To explain (non-blazar) variability, models include accretion disk instabilities (e.g., Kawaguchi et al. 1998), so-called Poissonian processes, such as multiple supernovae (e.g., Terlevich et al. 1992), and gravitational microlensing (e.g., Hawkins 1993). Since absorption has been seen to vary significantly on timescales of about a month, then some fraction of quasar flux variability should be due to absorbers. However, this does not require that more absorbed QSOs are more variable. Indeed, BALQSOs show no different variability properties than QSOs generally (Vanden Berk et al. 2004). Although the absorbers discussed here are warm (ionized), dust may also be expected to contribute to varying degrees which would contribute to the reddening of dimming events. According to Elvis et al. (2002), quasar outflows are natural dust producers. Since quasars are expected to be dustier at early cosmological times (Wilman et al. 2000), this may naturally explain the correlation of variability with redshift.

8. CONCLUSIONS

[4] We note that spectral differences are seen in Mg II in Fig 1a, and Mg II absorption is the criterion for a loBAL designation.

[5] Such lines are also seen in emission in other types of AGN, but are most easily detected when narrow, for example in Narrow Line Seyfert 1s like IZwI (Laor et al. 1997) and quasars like 2226-3905 (Graham et al. 1996).

We propose that small shifts in line-of-sight to quasars afforded by gravitational lensing can yield noticeable differences in spectroscopic line profiles, due to lateral fine structure in quasar absorbing outflows. Our hypothesis that lens-aided multi-angle spectroscopy of SDSS J1004+4112 probes a rotating, generally smooth, sheet-like flow with small-scale lateral spatial structure is consistent with these facts: (1) spectroscopy of lensed BALQSOs generally shows similar BAL trough profiles, but exceptions are known (2) significant absorber column differences can exist between sightlines to lensed BALs (3) absorption columns to individual quasars are known to vary significantly on timescales of hours to years (4) one component of SDSS J1004+4112 shows a UV emission line blue wing enhancement that is spectroscopically consistent with an unveiling event

Models of multi-epoch spectroscopic observations of lensed quasar images are necessarily convolved with models of intrinsic quasar variability, and with the as-yet poorly constrained structural parameters of the emitting/absorbing regions. Microlensing holds some promise for resolving the structure of the BELR in quasars. Unfortunately, detailed and accurate lens models are required. Worse, the size, mass, and velocity of the microlensing caustic will remain poorly constrained because microlensing depends on events (caustic crossings) that are fundamentally unpredictable and irreproducible, requiring a statistical approach to deconvolve the BELR structure. In contrast, if the LAMAS dominates over microlensing, then only the easily-measured angular separation affects the observations.

The most common proposed causes of spectroscopic differences in lens components (time variability and microlensing) are both proven phenomena, while LAMAS is not. LAMAS is distinguishable in several ways from these, and we propose several tests above. The addition of LAMAS to the mix may seem to muddy the waters, but LAMAS should be taken seriously until disproved, and may in fact provide direct geometric information about the internal structure of AGN that has long eluded us.

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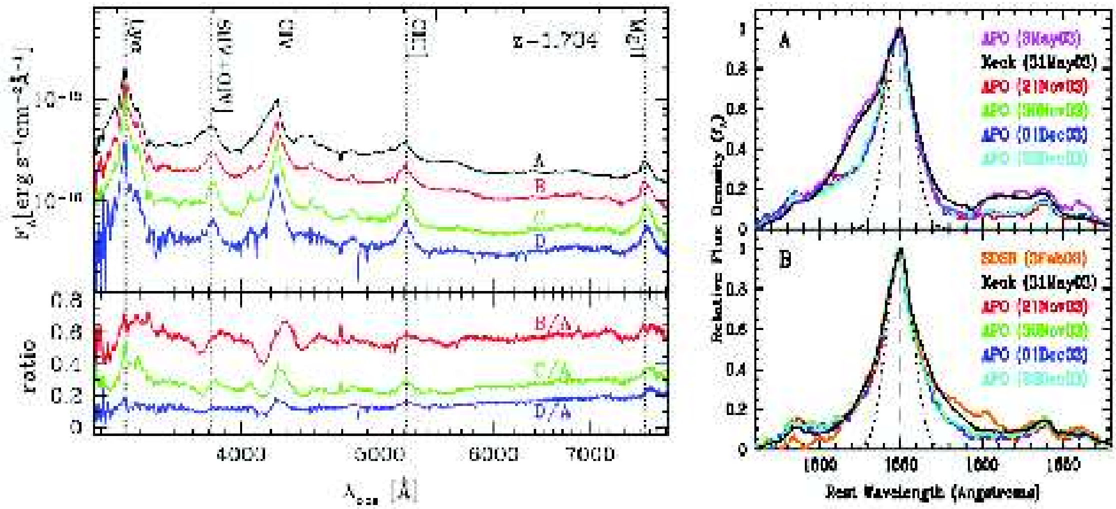

FIG. 1.— **SDSS J1004+4112 SPECTRA** *(a)* At left, spectra of the 4 quasar images of SDSS J1004+4112 rescaled for clarity (top) reproduced from (Oguri et al. 2004). The blue wings of emission lines are enhanced in *A*, most notably in C IV. The bottom panel highlights the differences, showing the ratio of each of *B*, *C*, and *D* to the *A* component spectrum. *(b)* In the right panel, seven epochs of the C IV emission line of SDSS J1004+4112 are reproduced directly from Richards et al. (2004). The spectra have been smoothed, renormalized so their peaks match, and are shown with a scaled Gaussian for reference (dotted line). The blue wing bump is apparent in the first 2 epochs of the *A* spectrum. Even after 21 Nov 2003, *A* maintains a strong *blue asymmetry*. The blue bump in component *A* reappeared in 2004 (Richards, Johnston, & Hennawi 2004; Wisotzki et al. 2004).

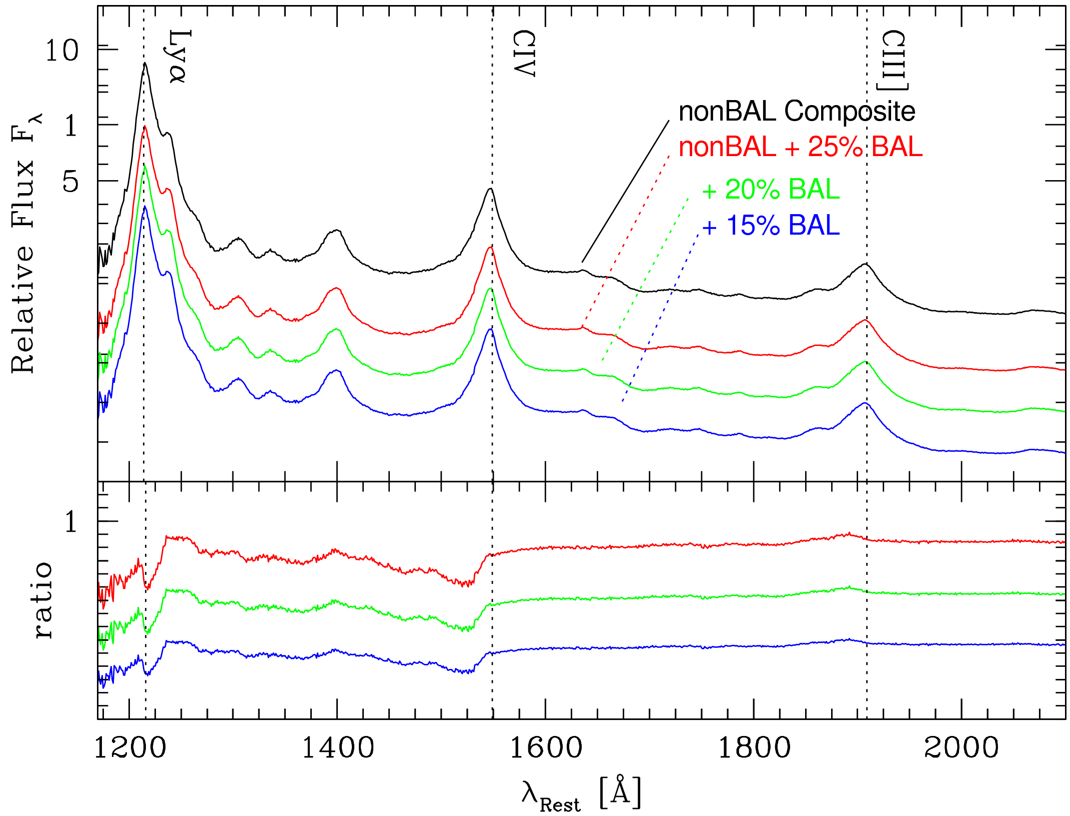

FIG. 2.— TOP: A rest-frame non-BAL composite spectrum from the SDSS from (Reichard et al. 2003) (black line), along with composite spectra we generated by adding 25, 20, and 15% of the SDSS high-ionization BAL composite spectrum (3 spectra below as marked). We have taken the logarithm of flux and offset the spectra for clarity, and we highlight just the region from Lyα to CIII], where the differences are most apparent. No BAL troughs are evident even in the 25% BAL spectrum. BOTTOM: The lower panel shows the ratio of these 3 part-BAL composite spectra to the non-BAL composite. While features may differ in detail, note the overall similarity to the spectral ratios seen in Figure 1 for SDSS J1004+4112.

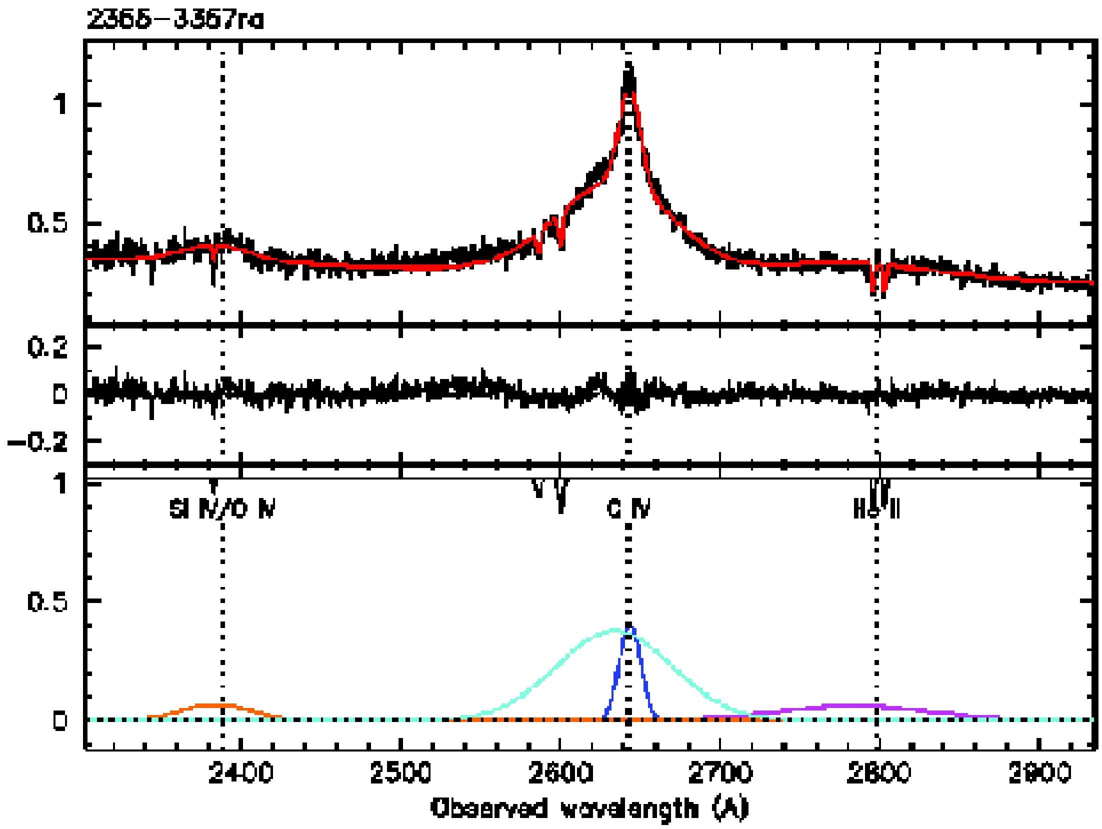

FIG. 3.— **2355–3357** C IV region of the spectrum of the quasar PKS J2355-3357, with multi-component fits from Kuraszkiewicz et al. (2002). The blue wings of C IV emission line is enhanced here, with a profile similar to that in SDSS J1004+4112.

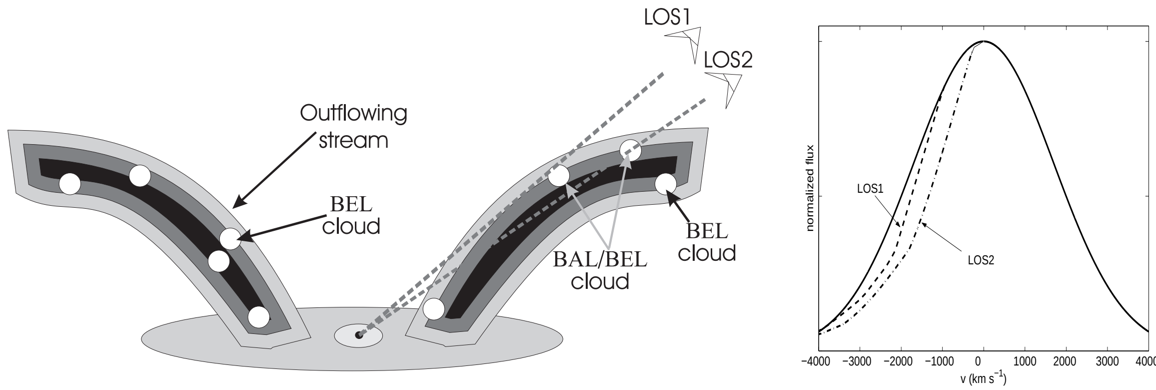

Fig. 4.— **ABSORBER MODEL.** *LEFT:* A cartoon of a stratified wind outflow model (Murray & Chiang 1997; Elvis 2000; Everett et al. 2002) shows 2 observers at slightly different line-of-sight angles to the outflow. In these models, wind-embedded clouds/streams act as emitters (absorbers) when we look at (through) them. *RIGHT:* A Gaussian emission line absorbed by a standard BAL outflow model (e.g., Arav 1999) along 2 slightly different sightlines as shown at left.