To appear in the *Astrophysical Journal*

Discovery of a Classic FR-II Broad Absorption Line Quasar from the FIRST Survey

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ABSTRACT

We have discovered a remarkable quasar, FIRST J101614.3+520916, whose optical spectrum shows unambiguous broad absorption features while its double-lobed radio morphology and luminosity clearly indicate a classic Fanaroff-Riley Type II radio source. Its radio luminosity places it at the extreme of the recently established class of radio-loud broad absorption line quasars. Because of its hybrid nature, we speculate that FIRST J101614.3+520916 is a typical FR-II quasar which has been rejuvenated as a broad absorption line (BAL) quasar with a Compact Steep Spectrum core. The direction of the jet axis of FIRST J101614.3+520916 can be estimated from its radio structure and optical brightness, indicating that we are viewing the system at a viewing angle of $\gtrsim 40°$. The position angles of the radio jet and optical polarization are not well-aligned, differing by $\sim 20° - 30°$. When combined with the evidence presented by Becker and coworkers for a sample of 29 BAL quasars showing that at least some BAL quasars are viewed along the jet axis, the implication is that no preferred viewing orientation is necessary to observe BAL systems in a quasar's spectrum. This, and the probable young nature of compact steep spectrum sources, leads naturally to the alternate hypothesis that BALs are an early stage in the lives of quasars.

Subject headings: quasars: individual J101614.3+520916; quasars: absorption lines; quasars: general

1. Introduction

It was long believed that a quasar could not be radio-loud and simultaneously have broad absorption lines in its optical spectrum (Stocke et al. 1992; Hamann, Korista, & Morris 1993).

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Over the past several years, the existence of quasars exhibiting both properties has been firmly established (Becker et al. 1997; Brotherton et al. 1998; White et al. 2000; Becker et al. 2000). We report here the most striking example to date of a radio-loud BAL quasar at z = 2.455, FIRST J101614.3+520916, which is not only extremely radio-loud but has a classic Fanaroff-Riley Type II (FR-II; Fanaroff & Riley, 1974) morphology with very bright radio lobes.

About 10% of the known quasars exhibit BAL outflows in their spectra (though the actual fraction depends heavily on how samples are selected, see Becker et al. 2000). This has been generally interpreted as BAL quasars being ordinary quasars viewed along a line of sight grazing the optically thick torus which surrounds the massive black hole engine (Weymann et al. 1991). The broad, highly blueshifted absorption is postulated to arise from clouds which are evaporated from the torus and accelerated outward by radiation pressure. In this picture, however, the apparent dichotomy of strong radio emission and the BAL phenomenon is extremely puzzling. There is no obvious reason in the orientation picture for radio emission to be suppressed, especially that from extended radio lobes. Additionally, typical BAL quasars have emission line and continuum spectral properties indistinguishable from ordinary quasars, in both the optical and radio (Stocke et al. 1992; Weymann et al. 1991; Barvainis & Lonsdale 1997). A number of possible explanations for the lack of radio-loud BALs – free-free absorption, frustrated jets, small scale structure in the accretion region – have been suggested (Stocke et al. 1992; Begelman, de Kool, & Sikora 1991; Boroson, Persson, & Oke 1985), but all are problematic. So perhaps it is not surprising that radio-loud BALs have finally been found.

This shift in understanding is being driven by studies which are probing new parts of parameter space: the FIRST Bright Quasar survey (FBQS; Gregg et al. 1996; White et al. 2000) relies on unprecedentedly faint radio fluxes of 1 mJy for candidate selection. The only other significant sample of radio-loud BALs, that of Brotherton et al. (1998) which found 5, also used a faint radio flux-limited sample (down to 2.5 mJy) from the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) to select quasar candidates. These studies are the first which are radio-sensitive enough to probe the transition region between radio-quiet and radio-loud quasars with good statistics. The radio properties of the BAL quasars, both radio-quiet and loud, present serious challenges to the current understanding of the quasar phenomenon.

FIRST J101614.3+520916 (hereafter J1016+5209) is a BAL quasar which we have found in an ongoing project to extend the FBQS from a limiting magnitude of E=17.8 to E=19. With the discovery of this object, any remaining uncertainty over whether a BAL quasar can be radio-loud is completely removed. Further, because of its FR-II morphology, some constraints can be placed on the viewing angle and orientation of the system. The properties of J1016+5209, taken together with the general results of the BAL quasar study of Becker et al. (2000), may call for a fundamental alteration of the commonly accepted unification-by-orientation scheme, or at least how the BAL phenomenon fits into the general quasar model.

The only other object known which may be similar to J1016+5209 in combining the characteristics of BALs with FR-II radio morphology is the z=0.240 quasar PKS 1004+13 (Wills, Brandt, & Laor 1999). PKS 1004+13 is not as extreme in its radio-loudness nor in the strength of its broad absorption (about which there is some remaining doubt due to the low S/N of the defining IUE spectrum), but if real, there are now two members of this hybrid class.

2. Observations

A POSS-I stellar counterpart with E and O magnitudes of 18.6 and 20.2, respectively, lies within $0\rlap{.}''25$ of the radio source J1016+5209.[5] A 9Å resolution optical spectrum was obtained using the Low Resolution Imaging Spectrograph (LRIS, Oke et al. 1995) at the Keck Observatory in December, 1998. A longer exposure but lower resolution ($\sim$ 20Å) LRIS spectrum was taken at Keck in June, 1999 (Figure 1). Both spectra clearly show prominent broad absorption features. The emission line redshift is 2.454 based on the fitted peak of C III] 1909 which is unaffected by BAL features, though it may be contaminated by Fe III, Si III], and Al III emission.

A second, higher S/N, 9Å resolution spectrum was obtained with LRIS in November, 1999. A close look at these data plotted in velocity space (Figure 2), shows an overall similarity between the C IV and Si IV BAL systems, though they differ in some details. Both C IV and Si IV exhibit a very broad system at $\sim -15,000$ $\mathrm{km\,s^{-1}}$ and deeper but more complex absorption system at velocities from 0 to -8000 $\mathrm{km\,s^{-1}}$. The broad C IV feature extends from ~ -8500 $\mathrm{km\,s^{-1}}$ to velocities of at least -17,200 $\mathrm{km\,s^{-1}}$ from the line center, possibly to -20,000 $\mathrm{km\,s^{-1}}$, at a depth $\gtrsim$ 10% of the continuum. Both Si IV and C IV also have significant absorption to the red of the line centers, by $\sim$ 1000 $\mathrm{km\,s^{-1}}$. The C IV ($\lambda\lambda$ 1548.2, 1550.8) doublet is separated by only $\sim$ 500 $\mathrm{km\,s^{-1}}$ while the Si IV ($\lambda\lambda$ 1393.8, 1402.8) doublet is separated by a much greater 1920 $\mathrm{km\,s^{-1}}$; three obvious velocity systems seen in both species are marked in Figure 2. The LRIS spectral resolution is comparable to the redshifted separation of the C IV doublet (8.5Å), but even the relatively narrow absorption trough at -6500 $\mathrm{km\,s^{-1}}$ has a FWHM of 23Å, about twice as broad as the instrumental resolution convolved with a single C IV doublet, indicative of broad or multiple components. The Si IV doublet is easily split and the widths of the narrow individual lines are consistent with the instrumental resolution. In addition to the narrow features, the general continuum level in the velocity interval 0 to -10,000 $\mathrm{km\,s^{-1}}$ is depressed by very broad absorption comparable in depth to the higher velocity BAL.

Using the C IV region, we have calculated the "BALnicity" index of J1016+5209 to be 2401 $\mathrm{km\,s^{-1}}$ (see Appendix A of Weymann et al. 1991). The BALnicity index (BI), though a quantitative measurement, is sensitive to subjective considerations, particularly continuum placement. For J1016+5209, the regions around -9000 and -5000 $\mathrm{km\,s^{-1}}$ (Figure 2) are particularly important;

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[5]These magnitudes are on the "corrected" APM system of White et al. (2000); photographic O and E are comparable to the more familiar B and R bands. Galactic reddening in this direction is insignificant, $A_V = 0.005$.

if counted as continuum, then the BI drops to $\sim$ 1600 $\mathrm{km\,s^{-1}}$, based solely on the very broad absorption extending from -17,200 to -8500 $\mathrm{km\,s^{-1}}$. Even this lower value is well within the ranks of other BAL quasars (Weymann et al. 1991).

As an ultimate test of its BAL nature, we obtained a high resolution spectrum of J1016+5209 in 2000 April, using the Echelle Spectrograph and Imager (ESI; Epps & Miller 1998) on the Keck II telescope. With a $1''$ slit, the instrument delivers a dispersion of 0.15Å to 0.3Å per pixel over a wavelength range of 3900 to 10900Å, highly oversampling the $\sim$ 1.5Å resolution spectrum. In Figure 3, we show the 4800 to 5500Å (restframe 1390 to 1590Å) region from the 1800s integration ESI spectrum, smoothed with a 9-pixel box, appropriate for the high oversampling, to improve the S/N. Overplotted is the LRIS spectrum from Figure 2. The S/N of the ESI spectrum is somewhat lower, and there is some additional structure in the depths of the BAL features, as might be expected from higher resolution data. But it is apparent that over the velocity range -17200 to -1500 $\mathrm{km\,s^{-1}}$ ($\sim$1460-1540Å rest wavelengths), none of the broad absorption breaks up into discrete narrow-line systems, confirming the BAL nature of J1016+5209. An example of what might be expected if the BAL regions in J1016+5209 did break up into discrete narrow-line clouds can be seen in the right panel inset of Figure 3 which shows the striking increase in resolution provided by the ESI spectrum for the intervening Mg II system, a truly narrow-line absorber. The only place where the BAL troughs do resolve into discrete components is at 5330Å (observed), but this is within $\sim$ 1400 $\mathrm{km\,s^{-1}}$ of the C IV peak and hence does not contribute to the "BALnicity" index.

We have also obtained spectropolarimetry with Keck and LRIS in 2000 January, as part of a broader program to obtain spectropolarimetry for all of the FBQS BAL quasars. J1016+5209 is polarized at the 2.5% level, rising gradually from less than 2% at 8000Å (2350Å rest) to about 3% at 4200Å (1250Å rest). The polarization position angle varies from 85° to 75° over the same wavelength interval. These polarization characteristics are typical of BAL quasars (Hines & Wills 1995; Goodrich & Miller 1995; Cohen et al. 1995). We will discuss the polarization properties of J1016+5209 in more detail in a future paper.

A contour plot of the FIRST survey 1400 MHz radio image of J1016+5209 is displayed in Figure 3a. This field has the typical FIRST [6] survey image characteristics: $5''$ resolution and 0.15 mJy rms noise. The core radio component associated with the quasar is marginally resolved, with a deconvolved size of $4''$, and has a flux density of 6.5 mJy. It is bracketed by two bright radio sources of 131 and 39 mJy, both slightly resolved in the FIRST data. We interpret these as edge-brightened radio lobes, making J1016+5209 a classic triple radio source with FR-II morphology and a total flux density of 177 mJy. The contours in Figure 3a suggest that there is a physical connection between the core and the brighter lobe. The total angular distance between lobe centers is $45''$ at a position angle of 146°. The radio source is bright enough to appear in several other radio surveys. The NVSS (Condon et al. 1998) lists a 20cm flux of 174 mJy for this object, indicating that FIRST adequately detects all of the flux and also that the source is probably not highly variable

[6]The FIRST Survey World Wide Web homepage is http://sundog.stsci.edu

on timescales of a few years. The 92 cm WENSS survey (Rengelink et al. 1997) measured a total flux density of 850 mJy. The source is also detected in the 6 cm Greenbank (Becker, White, & Edwards 1991) survey with a total flux density of 44 mJy. The WENSS and Greenbank data yield a global spectral index of $\alpha = -1.1$ (where $S_\nu \propto \nu^\alpha$), dominated by the bright lobes.

In 1999 July, a $0\farcs25$ resolution Very Large Array[7] (VLA) image of J1016+5209 was obtained in the A-array at 3.6 cm wavelength. The core is just marginally resolved with a fitted flux density of 1.84 mJy in this new image (RMS of 0.078 mJy); however, the northwest lobe shows an extended hotspot (Figure 3b) with a flux of 13.8 mJy and deconvolved size of $0\farcs59 \times 0\farcs15$. These are lower limits as flux on scales greater than a few arcseconds will be resolved out. The position angle of the major axis of the resolved hotspot is $140\fdg3 \pm 0\fdg6$; the position angle of the quasar from the hotspot location is a nearly identical $140\fdg8$, indicating that the radio lobe emanates from the quasar and is not a separate source. The southeast lobe is not reliably detected in the A-array data, probably because it is too diffuse.

We observed J1016+5209 yet again with the VLA in 1999 November using the B-array at a wavelength of 3.6 cm, this time obtaining polarization information as well (Figure 4). Because data were taken at only one frequency, we are unable to correct for Faraday rotation; however, since our measurements were at high frequency, this is expected to be small since the angle of rotation $\theta \propto \lambda^2$. In fact, the orientation of the magnetic field lines is as expected for a double-lobed FR-II source, parallel to the jet axis until reaching the hotspots, where it becomes perpendicular to the jet, indicating a shock-compressed field at the ends of the source.

Flux measurements at 8.46 GHz are: North hotspot/lobe = 18.6 mJy, Core = 2.1 mJy ($\sim 4\%$ polarized with a position angle of $54^\circ \pm 9^\circ$), South hotspot/lobe = 3.8 mJy. The lobe fluxes are lower limits as there will be some flux missing from the map on scales $> 10''$. The core is strongly polarized, 4% at 8.4 GHz, perhaps greater if there is any depolarization. If the rotation measure is high, which could be the case if J1016+5209 is embedded in a thick shroud (see §3.1), depolarization of the core radio source could be significant. Comparing these flux density estimates to the FIRST survey numbers, the spectral indices are -1.10, -0.63, and -1.31 for the North lobe, Core, and South lobe, respectively.

3. Analysis and Discussion

The observed and derived properties of J1016+5209 are summarized in Table 1; we adopt $H_\circ = 50\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_\circ = 0.5$. The radio properties are extreme in several respects: J1016+5209 has a total radio luminosity of $10^{34.4}$ ergs $\mathrm{cm^{-1}s^{-1}Hz^{-1}}$, the highest of any known BAL quasar. Using the definition of Stocke et al. (1992), we compute log(R*), the ratio of radio-

[7] The Very Large Array is a facility of the National Radio Astronomy Observatory, operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

to-optical brightness, as 3.4, using the global radio spectral index of -1.1 and optical spectral index of -1. This value of log(R*) is also an extreme for known BAL quasars, and is at the high end of the distribution even for radio-selected non-BAL quasars (White et al. 2000). In fact, *even if we consider only the core radio flux of J1016+5209, it is still radio-loud* with log(R*) = 2.0.

It is possible to estimate the angle between our line of sight and the jet axis in J1016+5209 using the "core-dominance" measure defined by Wills & Brotherton (1995) as $\log(\mathcal{R}) = \log(L_R) + 0.4 * M_V - 13.69$, where L_R is the 5 GHz radio luminosity (of the core alone, Table 1) in units of W Hz^{-1}. The $M_B = -26.2$ (Table 1) (we have assumed the B and O passbands to be equivalent); we adopt $B - V = 1$ as a reasonable estimate of its color based on the $O - E$ of 1.6. This yields $\log(\mathcal{R}) \approx 1.3$, placing it at the extreme of orientations in the Wills & Brotherton sample where viewing angles are large, $> 40^\circ$, but not well constrained. Even so, it is additional evidence that J1016+5209 is viewed well away from the jet axis.

3.1. The orientation model cannot explain BAL quasars

A popular explanation for the presence of BALs in a minority ($\sim 10\%$) of the quasar population is that quasars must be viewed at a preferred orientation to exhibit BALs in their spectra, along a line of sight roughly in the plane of the quasar accretion disk. To test this hypothesis, it is necessary to establish the orientation of BAL quasars; this can be done through radio observations. The FBQS is finding a surprisingly large number of BAL quasars for a radio-selected sample (Becker et al. 2000) with a frequency at least as great as that of the optically selected Large Bright Quasar Survey (Hewett, Foltz, & Chafee 1995). A large sample of radio-emitting BAL quasars offers the chance to investigate BAL viewing orientations.

The present sample of ~ 25 FBQS BAL quasars consists predominantly of unresolved compact radio sources, and, even the few that are slightly resolved still show no outright structure (such as lobes) on the angular scale of the FIRST survey (a few arcseconds). This differs markedly from the radio morphologies of a non-BAL subsample from the FBQS, matched in redshift and radio flux, where 30% of the non-BAL quasars show extended radio structure (Becker et al. 2000). Even without direct evidence from the radio morphology, some information on orientation can be obtained from radio spectra. The radio spectral indices of the 29 BALs in the FBQS vary widely, from -1.2 to +0.7, with 8 flatter than -0.5, and several more with indices of -0.5 (Becker et al. 2000). The scatter in spectral index is consistent with the findings of Barvainis & Lonsdale (1997) for the radio spectral indices of a smaller sample of 15 BAL quasars. If the bulk of the radio emission is from a relativistic jet, the objects with flat spectra are naturally interpreted as viewed close to the radio jet axis, while the steep-spectrum objects are those seen at larger viewing angles to the jet axis. This analysis is at odds with the model in which quasars must be viewed at a particular orientation to see BALs (e.g., Weymann, et al. 1991; Hines & Wills 1995; Goodrich & Miller 1995; Cohen et al. 1995).

Our results for J1016+5209 support the conclusion that a preferred viewing angle is not necessary to produce a BAL quasar. This object has unambiguous properties of both a BAL and a radio-loud FR-II. The radio spectral indices of the core and lobes exhibit the expected behavior, with the core flatter than the lobes, and the orientation is clearly well away from the jet axis, quite the opposite from the flat-spectrum BAL quasars. We conclude that a preferred line of sight is not necessary to observe BALs in quasars, and suggest that the alternative view that the BAL phenomenon is a stage, probably early, in the development of the quasar is more consistent with our data. Becker et al. (2000) speculated that the compact radio size of the BAL quasars implied a relatively young age for the BAL phenomenon: any radio jet is still in the process of emerging from a thick cocoon of material, and extended radio lobes on the 100 kpc scale have not had time to develop, as has been suggested by Briggs, Turnshek, & Wolfe (1984), Voit et al. (1993), Egami et al. (1996), and others. This suggests a possible link to compact steep spectrum (CSS) or gigahertz-peaked Spectrum (GPS) radio sources (e.g., O'Dea 1998; also see below, §3.2).

Hamann et al. (1993) argue from detailed modeling of BAL spectra that the covering factor q, the fraction of the sky covered by BAL regions as seen from the central source, is ~ 0.1. Coupled with the statistical result that $\sim$ 10% of all quasars have BALs, their modeling result strongly implies that the conditions which give rise to the BAL phenomenon are present in every quasar and we simply do not see it 90% of the time because our line of sight does not pass through the BAL region. One possible way to reconcile this with the conclusion drawn above – that BAL quasars are *not* seen at any particular orientation – is to relax the usual assumption that BAL clouds are spatially concentrated near the plane of the obscuring torus surrounding the central engine. Arranging this could be problematic, however, if the BAL clouds originate in the torus region and are accelerated radially outward, which would naturally work to confine them to the plane of the torus.

Perhaps a more likely explanation of the radio results for the FBQS sample, which imply covering factors of approximately unity, is that the critical assumption of the Hamann et al. models that photons are conserved is not applicable. Voit et al. (1993) argue that BAL quasars which have very weak or absent C IV emission cannot be plausibly explained by small covering factors. Rather, the C IV photons are destroyed by repeated scatterings during their passage through a spherical shell of gas and dust. Such a shell does not even need to be very optically thick to reduce the C IV and other resonance emission lines such as Mg II to a negligible amount, as long as the dust and C IV ions are co-spatial. J1016+5209 certainly has weak resonance emission lines and its continuum is quite red for a quasar. Adopting the "starburst" reddening law of Calzetti et al. (1994), we estimate that J1016+5209 has $A_V \approx 0.75$, by comparing the shape of the rest frame continuum between 1600Å and 2200Å with that of a composite quasar spectrum (Brotherton et al. 2000) from the FBQS. Figure 5 displays the observed and dereddened spectrum of J1016+5209 and the quasar composite. The derived A_V implies an optical depth from dust at 1550Å of ~ 2.3. In the simple scattering/absorption model that Voit et al. propose, this is sufficient to destroy the large majority of resonance line photons and provides a covering factor ~ 1.

The significant reddening from dust in J1016+5209 has further implications. First, high reddening is generally associated with BAL quasars which show absorption from low ionization species such as Mg II 2800, the "LoBAL" quasars (Sprayberry & Foltz 1992). Such objects generally also have strong Fe II emission (Weymann et al. 1991). Inspection of Figures 1 and 5 reveals that the Mg II emission is certainly much weaker in J1016+5209 than in the composite quasar, perhaps because of weak BALs. There is also a noticeable enhancement of Fe II emission to the blue of Mg II, which may in fact be partly responsible for filling in any possible Mg II BALs. In the higher resolution Keck spectrum of J1016+5209, there are weak absorption lines which correspond to Al III $\lambda\lambda 1854.7, 1862.8$. The C III] emission feature in J1016+5209 is broader and not as peaked as that of the composite quasar; this can be attributed to emission from Fe III $\lambda\lambda 1895, 1926$. We conclude that J1016+5209 has some properties in common with LoBAL quasars.

All of these considerations again lead us to prefer a picture where BAL quasars are emerging from a dusty cocoon of material, probably at an early phase in their history. The statistic that BAL quasars make up 10% of the quasar population suggests that this phase lasts about 10% of the total quasar lifetime. As LoBALs are generally more highly reddened, they are an earlier period in the emergence of a quasar in this model than HiBALs.

Correcting for the dust extinction makes J1016+5209 brighter at 2500Å by 1.8 magnitude, and so reduces its radio-loudness from $\log(R^*) = 3.4$ to 2.7. This still leaves it as the most radio-loud BAL known.

3.2. J1016+5209 as a Transition or Hybrid Object

J1016+5209 is the only FR-II quasar among the ~ 50 BAL quasars which have been discovered in follow-up to the FIRST survey ($\sim$ 25 from Becker et al. 2000, plus an additional $\sim$ 25 in subsequent follow-up, unpublished). In the FBQS, roughly 12% of $z > 0.5$ quasars exhibit double-lobe morphology (Becker et al. 2000) and an additional $\sim 10\%$ show at least some radio structure. Why are BAL quasars with large radio lobes so rare? One possibility is that J1016+5209, and its potential low-z counterpart PKS 1004+13, are transition objects, on the way to becoming normal (non-BAL) FR-II quasars, caught in a relatively brief period during which the two phases co-exist. Another possibility is that J1016+5209 is a hybrid object, perhaps an old FR-II source which has recently been rejuvenated as a CSS/BAL source in its core.

Even though the high resolution ESI spectrum shows that the BAL features of J1016+5209 in general do not break up into myriad cloudlets, the lowest velocity trough does exhibit more structure in its depths than does the trough at -15000 $\mathrm{km\,s^{-1}}$, and at one location, v=-1400 $\mathrm{km\,s^{-1}}$, a narrow inter-cloud continuum is nearly resolved (Figures 2 and 3). The absorption within 9000 $\mathrm{km\,s^{-1}}$ of the emission line redshift is reminiscent of the more extreme examples of the class of "associated absorber" (AA) quasars (Foltz et al. 1988). Were it not for its prominent BAL trough at -15000 $\mathrm{km\,s^{-1}}$, J1016+5209 might fall more naturally into the AA class, though it would be by far the most extreme example. A somewhat similar AA is PKS 1157+014 (Wright et al. 1979), a z=1.9, radio-loud quasar. It has two moderately broad absorption troughs at -6500 and 0 $\mathrm{km\,s^{-1}}$, not unlike the corresponding but more extreme spectral regions of J1016+5209, even though BI=0 for PKS 1157+014. Whether such AA features, which are not broad enough to gain distinction as true BALs in the quantitative BALnicity definition of Weymann et al. (1991), are intrinsic to the quasar or generated in an intervening object has been debated for some time (Morris et al. 1986; Foltz et al. 1986). Recently, Aldcroft, Bechtold, & Foltz (1998) presented evidence for variability of the higher velocity outflow in PKS1157+014, perhaps resolving the argument in favor of the intrinsic case, at least for this well-studied example. This is consistent with the growing evidence that many systems which are currently thought to be intervening, especially in radio-loud quasars, are really intrinsic (Richards et al. 1999).

It may be that J1016+5209 is in transition from a BAL to a more normal radio-loud quasar, and that PKS1157+014 is representative of the next evolutionary phase of a radio-loud object such as J1016+5209. If the highest velocity absorber in J1016+5209, already not as deep, were to fade away first, leaving behind the lower velocity troughs, the result would be similar to PKS1157+014. Perhaps we have just happened to catch J1016+5209 in a relatively rare, short-lived state in which it exhibits BAL features while having already developed strong radio emission. This could occur in a brief period at the end of the evolution of a BAL in which the radio emission finally manages to erupt from confinement but the dense cocoon has not completely dissipated. During such dissipation, the BALs may eventually evolve into distinct cloudlets as hinted at here, driven by the ensuing outflows of ionized plasma accompanying the radio emission. That the central region of J1016+5209 is completely surrounded by turbulent absorbing material is supported by the presence of absorption occurring at velocities to the red of the rest frame Si IV and C IV by ~ 1000 $\mathrm{km\,s^{-1}}$.

This picture is consistent with the radio core of J1016+5209 having an unusually steep spectrum, $\alpha = -0.63$, and being unresolved at the $0\farcs25$ (~ 2 kpc) scale. These properties are reminiscent of CSS or GPS sources: the leading interpretation of CSS and GPS sources is that they are young radio objects, confined to a small region by dense gas but which evolve with time into extended radio sources with lobes as they escape confinement (O'Dea 1998), much like the picture of BAL quasars emerging from cocoons (Voit et al. 1993). This coincidence of attributes in J1016+5209 supports the notion that BAL quasars are an early evolutionary phase in the life cycle of a quasar. The polarization of CSS sources is typically higher than that of GPS sources, $\sim 5\%$ *vs.* 0.2% at 6cm (O'Dea 1998), so the $\sim 4\%$ polarization at 3.6cm for the core of J1016+5209 suggests that it is a CSS object, but low frequency data for the core alone are needed to confirm this. If it is a CSS, then J1016+5209 may exhibit the so-called "alignment effect" between its radio and optical structure (McCarthy 1993 and references therein); any possible connection with its BAL nature would be interesting in this context. The misalignment of the optical polarization and large-scale radio jet axes could be explained if on subarcsecond scales J1016-5209 has been reborn with a different jet axis.

Steep-spectrum cores, however, are not uncommon in high redshift, lobe-dominated quasars

(Lonsdale, Barthel, & Miley 1993). An alternative possibility is that J1016+5209 is a normal FR-II quasar in a very low density environment which allows rapid expansion of the radio lobes. If the radio lobes were expanding unimpeded at relativistic speeds, then the brighter, jet-side lobe should be significantly farther from the core, whereas just the opposite is seen. The arm-length ratio Q for J1016+5209, however, is 0.64, at the extreme low end of the distribution found by Scheuer (1995) for a sample of radio-luminous, double-lobed quasars. The asymmetry of J1016+5209 then is probably due to environmental rather than relativistic effects, implying that the lobes are not expanding freely and rapidly, and hence are not particularly young. If the radio source is expanding at speeds typical of FR-II radio sources, $\sim 0.1c$ (Arshakian & Longair 2000), the large extent of the lobes of J1016+5209, ≈ 350 kpc, suggests a fairly advanced age (for a radio source) of $\sim 10^7$ yr; PKS 1004+413 is also a large source, ≈ 475kpc in size, and so of comparable age.

If the core of J1016+5209 is a CSS or GPS object, the presence of larger scale, presumably older, very bright radio lobes (Figures 4 and 5) at a large distance from the central engine supports the hypothesis that quasars can be "reborn" and that perhaps both the BAL and CSS/GPS properties can occur repeatedly in a given object, but always early in any "on" cycle of AGN activity. In support of the rejuvenation picture, about 10% of GPS/CSS sources have extended emission (O'Dea 1998 and references therein), possibly from an earlier period of activity, now dissipated. It may be that J1016+5209 is in an early phase of rejuvenation, having particularly compact inner lobes which will grow, becoming a double-double radio source; a number of such objects are known (Schoenmakers et al. 2000). Higher resolution mapping of the core of the J1016+5209 is needed to test its GPS/CSS nature.

The interpretation of J1016+5209 as a rejuvenated quasar suggests that it may not be correct to compute its radio-loudness using the entire radio flux, at least not in the context of evaluating the "BAL-related" radio-loudness in its present incarnation. With the reddening correction and counting only the core flux, $\log(R^*) \approx 1.24$, still formally radio-loud, but not as exceptional as $\gtrsim 3$ for the total radio flux.

4. Summary

The properties of the quasar FIRST J1016+5209 stand out in several respects. It exhibits bona fide BALs in its optical spectrum while also having a classic FR-II radio-loud morphology. J1016+5209 is the most radio-loud and radio-luminous BAL quasar known. The only other object which may be of a similar nature is the less extreme, low redshift quasar PKS 1004+13 (Wills et al. 1999). The presence of distinct bright radio lobes and its low "core dominance" parameter implies that J1016+5209 is viewed well away from the jet axis, at an angle of $\gtrsim 40°$. Based on the large scatter in radio spectral indices, Becker et al. (2000) argue that BAL quasars are not viewed at any particular orientation, contrary to the popular orientation model. The relatively steep spectrum ($\alpha \approx -0.6$) and compact size ($< 0\farcs3$ at 3.6cm) of the radio core of J1016+5209 suggest that it is a CSS source, suggesting that J1016+5209 is young. This supports the alternate model of BAL quasars in which they are an early phase in the evolution of quasars. The 20°–30° misalignment of the optical and radio polarization axes is further evidence that J1016+5209 does not easily fit the orientation model for BAL quasars.

The large scale (350 kpc) FR-II radio lobes of J1016+5209 do not easily fit the picture of it being young, so we postulate that it is a rejuvenated quasar, possibly through a merger or interaction. If there is a newly created – perhaps even episodic – CSS source at the core of J1016+5209, higher resolution imaging at various wavelengths should reveal interesting connections among the various attributes (BALs, CSS, radio-loudness, FR-II morphology) that have come together in this one object.

We gratefully acknowledge D. Stern and H. Spinrad for obtaining the low resolution Keck spectrum of FIRST J1016+5209 and Willem De Vries for helpful comments. Some of the data presented here were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Keck Observatory was made possible by the generous financial support of the W.M. Keck Foundation. The FIRST Survey is supported by grants from the National Science Foundation (grant AST-98-02791), NATO, the National Geographic Society, Sun Microsystems, and Columbia University. Part of the work reported here was done at the Institute of Geophysics and Planetary Physics, under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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Table 1.

FIRST J101614.3+520916 Properties	
RA (J2000)	$10^h16^m14\overset{s}{.}3$
DEC (J2000)	$+52°09'16$
z	2.455
$O(\approx B)$	20.2
$E(\approx R)$	18.6
S_{20cm} core (mJy)	6.5[a]
S_{20cm} NW lobe (mJy)	131.1[a]
S_{20cm} SE lobe (mJy)	39.3[a]
S_{92cm} (mJy)	850[b]
S_{6cm} (mJy)	44[c]
Lobe-lobe axis PA (°)	146
Lobe peak-to-peak distance (″)	45
Total projected size (kpc)	350
M_B	-26.2 (-27.3)
$\log(L_{5GHz})$ Total (ergs $s^{-1}cm^{-2}Hz^{-1}$)	34.3
$\log(L_{5GHz})$ Core (ergs $s^{-1}cm^{-2}Hz^{-1}$)	32.9
$\log(R^*)$ (total)	3.4 (2.7)
$\log(R^*)$ (core only)	2.0 (1.2)

[a]FIRST survey (Becker et al. 1995)

[b]WENSS (Rengelink et al. 1997)

[c]Greenbank (Gregory et al. 1996)

Note. — Derived quantities assume $H_\circ = 50\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_\circ = 0.5$. Quantities in parentheses corrected for intrinsic extinction of $A_B = 1.1$

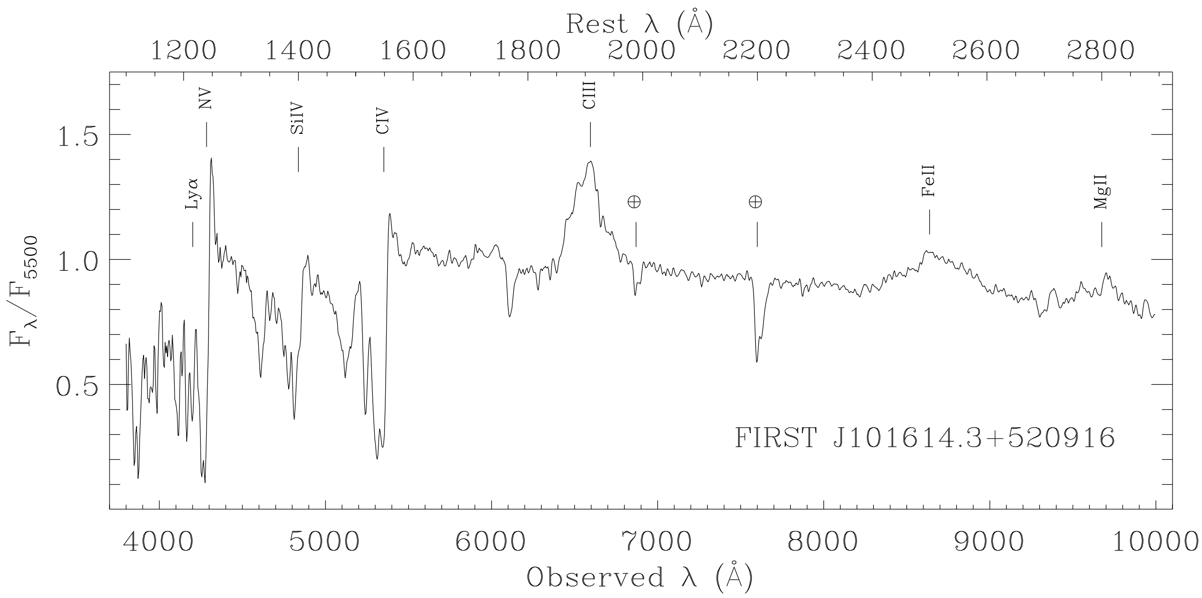

Fig. 1.— Low resolution spectrum of J101614.3+520916 obtained at Keck Observatory using LRIS. Prominent features are labeled. There is a relatively strong intervening Mg II 2800 absorption system at an observed wavelength of 6110Å (z = 1.182).

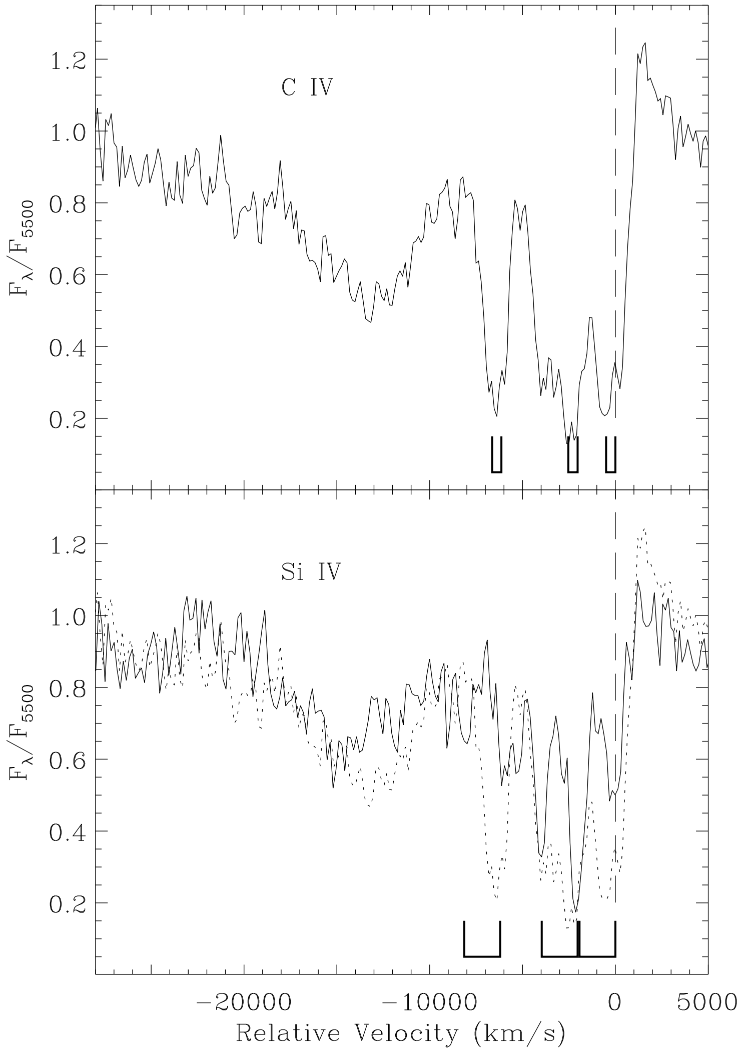

Fig. 2.— Close-up of the C IV and Si IV regions of the spectrum of FIRST J101614.3+520916, shown in velocity space appropriate for the rest frame of the red side of each doublet. The C IV region is repeated in the the lower panel as a dotted line for comparison.

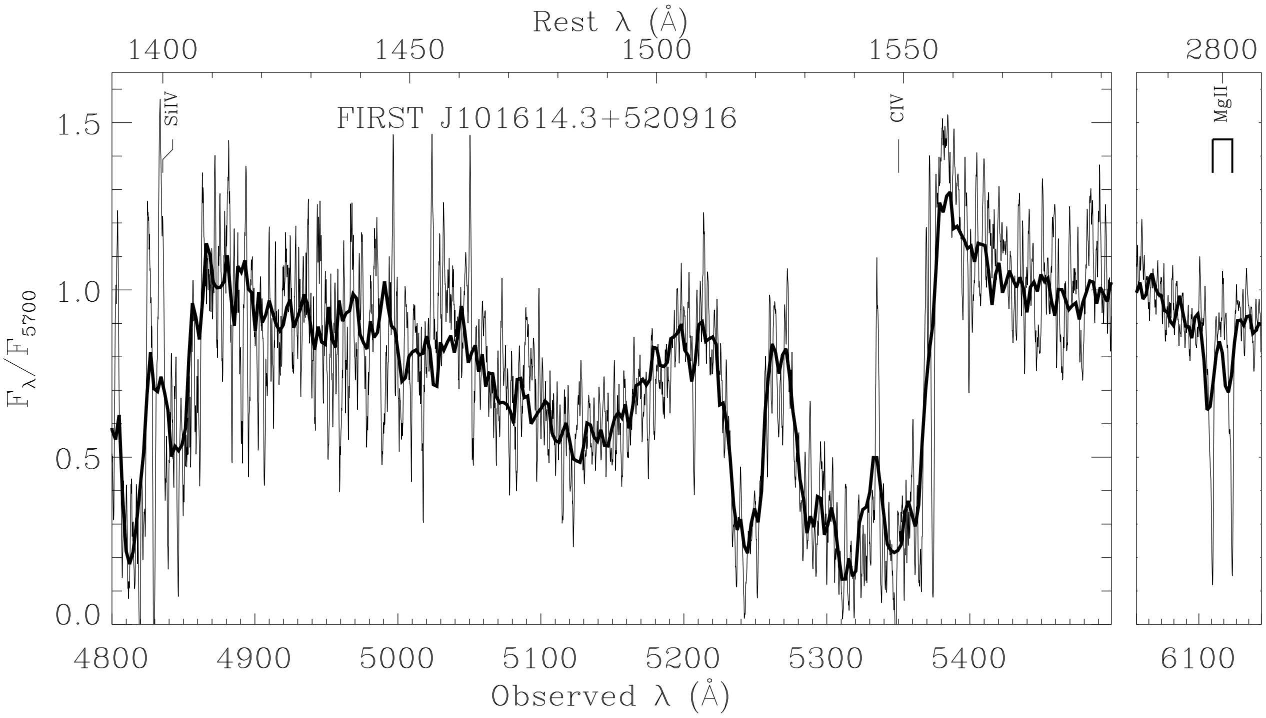

Fig. 3.— Keck 10m ESI spectrum of the C IV BAL region (thin line) in J101614.3+520916; the resolution is 1.5Å. Overplotted is the 9Å resolution LRIS spectrum (thick line) from Figure 2. The gain in resolution with ESI compared to LRIS is demonstrated by the small panel on the right showing the intervening Mg II absorber in each. The C IV absorption troughs do not break up into numerous individual unresolved cloudlets, confirming the BAL nature of J1016+5209.

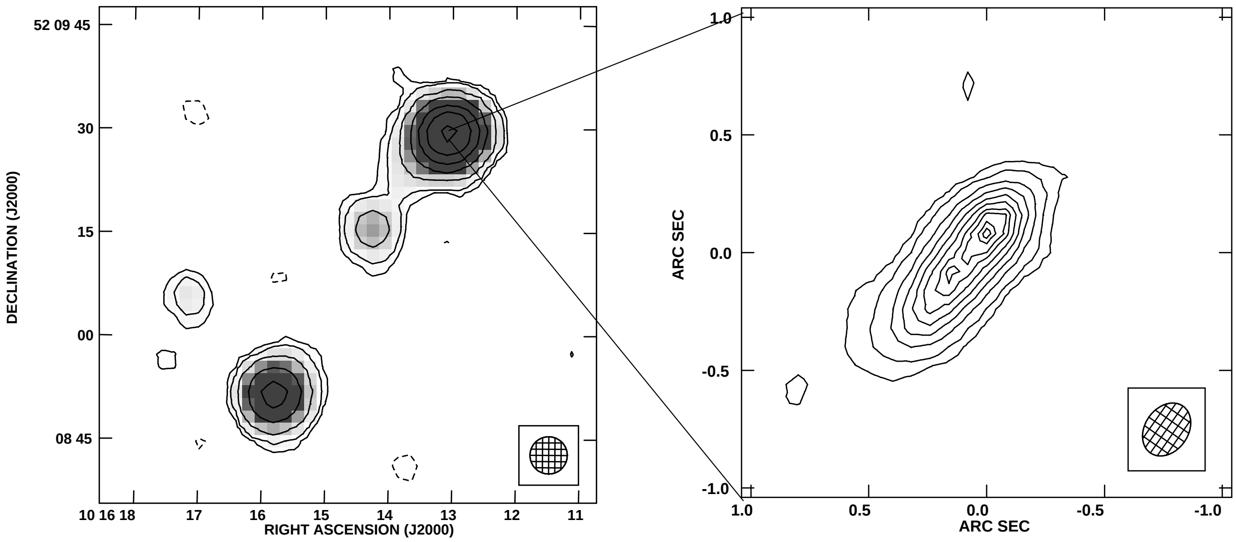

Fig. 4.— Left: FIRST survey 20 cm image of J101614.3+520916; contour levels are -0.5, 0.5, 1.0, 5, 10.0, 20.0, 50.0 and 100.0 mJy.
Right: A-array 3.6 cm image of the northwest lobe showing linear structure pointing directly back to the radio core, evidence that the two are physically associated and not a chance arrangement of radio sources. Contour levels are 0.24, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.35, 3.75, and 4.0 mJy; the map has an RMS of 0.078 mJy.

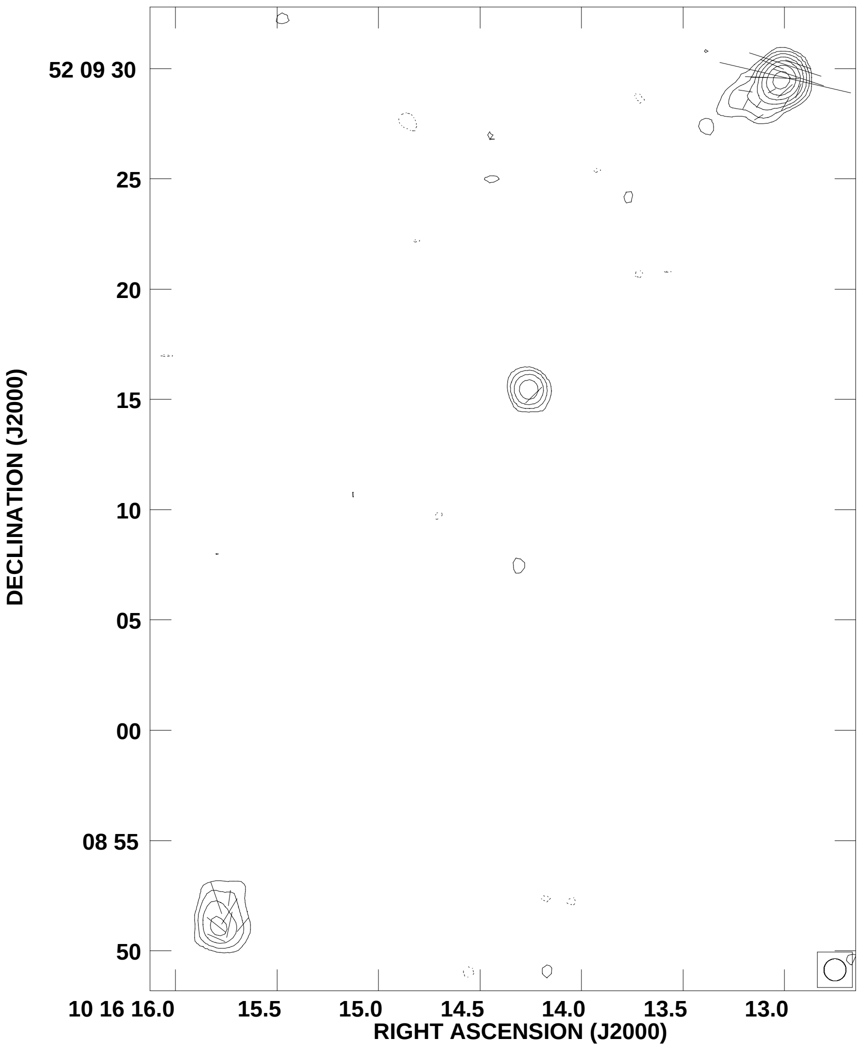

Fig. 5.— VLA B-array 3.6cm map of J101614.3+520916; contours are logarithmic, spaced by factors of two from ±0.15 mJy. The polarization vectors have been rotated by 90° to indicate the orientation of the magnetic field and are scaled so that a polarized flux of 0.1 mJy corresponds to a vector one arcsecond long. No corrections for Faraday rotation or depolarization have been made. Flux measurements at 8.46 GHz are: North hotspot/lobe = 18.6 mJy, Core = 2.1 mJy, South hotspot/lobe = 3.8 mJy.

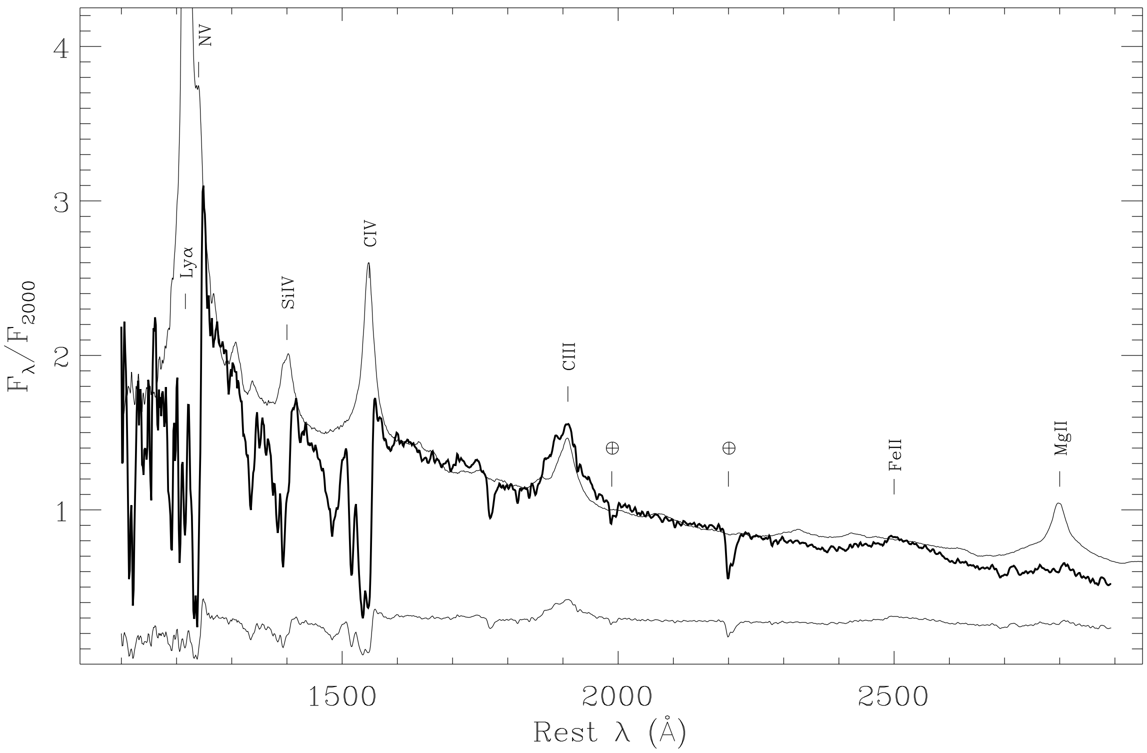

Fig. 6.— Dereddening the Keck LRIS spectrum of FIRST J1016+5209 (lower thin line) using $A_V = 0.75$ and the starburst reddening law of Calzetti et al. (1994) yields a good match (thick line) with the composite quasar spectrum (Brotherton et al. 2000) from FBQS (upper thin line). Prominent features are labeled; J1016+5209 has comparatively weak Mg II 2800, suggesting possible absorption by BALs, in turn possibly masked by Fe II emission which is common in LoBALs. The C III] 1909 emission profile also appears to be distorted relative to the composite; this is likely from Fe III, Si III, and Al III emission. The observed spectrum of has been scaled up by a factor of two for clarity.