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DISCOVERY OF A RADIO-LOUD/RADIO-QUIET BINARY QUASAR[1]

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ABSTRACT

We report the discovery of a small separation quasar pair (z = 0.586, O = 18.4, 19.2, sep. = 2.″3) associated with the radio source FIRST J164311.3+315618 (S_{1400} = 120 mJy). The spectrum of the brighter quasar (A) has a much stronger narrow emission-line spectrum than the other (B), and also stronger Balmer lines relative to the continuum. The continuum ratio of the spectra is flat in the blue ($\lambda_{obs} < 6000$ Å) at about 2.1, but falls to 1.5 at longer wavelengths. A K' image shows two unresolved sources with a flux ratio of 1.3. The different colors appear to result from the contribution of the host galaxy of B, which is evident from Ca II and high-order Balmer absorption lines indicative of a substantial young stellar population. New 3.6 cm VLA observations show that the compact radio source is coincident with quasar A (B is only marginally detected). We rule out the lensing hypothesis because the optical flux ratio is A/B $\approx$ 1.5–2 while the radio flux ratio is A/B $\gtrsim$ 40, and conclude that this system is a binary. Moreover, the radio-loud quasar is a compact steep spectrum source. FIRST J164311.3+315618A, B is the lowest redshift and smallest separation binary quasar yet identified.

Subject headings: galaxies: evolution, galaxies: interactions, quasars: emission lines, quasars: general

1. INTRODUCTION

Small separation quasar pairs at similar redshifts are closely scrutinized as gravitational lens candidates. While dozens of lensed quasars have been confirmed, wide separation (3″-10″) high-redshift O^2 pairs (both quasars are radio faint) are more problematic. Djorgovski et al. (1987) discovered PKS 1145-071, the first O^2R pair (one quasar is radio bright and the other is radio faint): PKS 1145-071 must be a binary because lensing cannot produce two images with extremely different flux ratios in the optical and the radio. The existence of O^2R quasar binaries, plus the fact that only some 10% of optically selected quasars are radio-loud, lead Kochanek, Falco, & Muñoz (1997) to make a statistical argument that most of the wide-separation O^2 lens candidates are actually binary quasars.

Understanding the frequency of binary quasars is important for interpreting lensing statistics. Such systems also provide clues to the origins or fueling of quasar activity, and why strong radio jets are found in some objects but not others. If galaxy interactions and mergers activate quasars (e.g., Sanders et al. 1988; Hernquist 1989; Mihos & Hernquist 1996), then the rapid evolution of the space density of quasars, and its peak during the epoch $z = 2-3$, may reflect the merger history of galaxies. If galaxies are assembled hierarchically, then quasars may trace galaxy evolution and star formation (e.g., Barnes 1998).

In a spectroscopic search for quasars detected by the FIRST survey (Faint Images of the Radio Sky at Twenty centimeters; Becker et al. 1995), we discovered a radio-loud, radio-quiet binary quasar system associated with the radio source FIRST J164311.3+315618 (hereafter FIRST J1643+3156). In this *Letter*, we describe our observations of this system and compare it to other confirmed binary quasars. We adopt H_0 = 50 km s^{-1} Mpc^{-1}, q_0 = 0. With z = 0.586 and a separation of 2.″3 (20 kpc), FIRST J1643+3156A, B is the nearest and smallest separation binary quasar known.

2. OBSERVATIONAL RESULTS

We identified FIRST J1643+3156 as a quasar candidate based on its radio emission (S_{1400} = 120 mJy, integrated flux density) in the FIRST survey, its stellar classification by the APM (e.g., McMahon & Irwin 1992) on both the blue (O = 18.0 mag.) and red (E = 18.0 mag.) POSS plates, and its blue color ($O - E = 0$). While the current limit of the FIRST Bright Quasar Survey (Gregg et al. 1996; White et al. 1999) is E = 17.8, we are observing fainter targets as part of the FIRST Faint Quasar Survey (Becker et al. 1998).

We observed FIRST J1643+3156 on 15 July 1998 (UT) with the Keck II telescope using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995). On the acquisition camera we noticed that there were two stellar objects separated by 2″ near the target coordinates. We obtained exposures of three minutes on the brighter southern component (A) and ten minutes on the fainter northern component (B). The 300 line mm^{-1} grating with a 1″ slit gave a resolution $\leq$ 10 Å. We employed standard data reduction techniques within the NOAO IRAF package, and used a standard star to divide out atmospheric features.

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The redshift of each is 0.586 based on [O II] λ3727 and [O III] λ5007, with a difference at the $\sim$100 km s^{-1} level. The broad Mg II λ2800 profiles are similar with FWHM = 3400$\pm$300 km s^{-1}, but the broad Balmer lines and narrow-line spectra differ. Quasar B also shows high-order Balmer and Ca II H and K absorption lines, and has a redder continuum (Fig. 1).

We took a K' image using NSFCAM at the IRTF on 22 August 1998, when conditions were photometric with 0$''$.8 seeing. The total on-source exposure time was 960 s. After linearization and flatfielding, the data were sky-subtracted, registered, and summed using DIMSUM[1]. Standard stars from Persson et al. (1998) were used to yield magnitudes on the CIT system. Component A has K'=16.6, B has K'=17.0, and both are unresolved.

The FIRST survey (resolution 5$''$) is insufficient to resolve the radio source or to determine definitively whether it is associated with component A or B. We obtained a 0$''$.7 resolution map on August 31, 1998 (UT) with the NRAO[2] Very Large Array (VLA) in the B configuration, at 3.6 cm, with 14 minutes exposure time. Data were calibrated and reduced in the standard way using the AIPS analysis package. The resulting cleaned map resolves a radio source of small angular extent ($\approx$ 1$''$.4, PA=71°). The peak and total flux densities are 16 mJy and 36 mJy, respectively.

We used the 9 nearest HST Guide Stars to obtain an astrometric solution on the Second Generation Digital Sky Survey with an RMS of $\sim$ 0$''$.1 (GSC 1.2 has a positional accuracy of 0$''$.3 $-$ 0$''$.4 per star). This solution was transferred to the IRTF image using 3 unresolved objects which appeared in both bands. The final 1σ absolute positional error is $\sim$ 0$''$.3. Figure 2 shows the centroid positions of components A and B (crosses) on the VLA 3.6 cm contour map. Quasar A is coincident with the compact radio source while Quasar B is associated with a marginally detected (0.4 mJy, 4σ) radio source. At 3.6 cm the peak-to-peak radio flux ratio is S_A/S_B=40.

FIRST J1643+3156 has been detected in other radio surveys, including: Westerbork Northern Sky Survey (393$\pm$47 mJy at 325 MHz; Rengelink et al. 1997), Texas (407$\pm$29 mJy at 365 MHz; Douglas et al. 1996), and the NRAO VLA Sky Survey (121$\pm$3.7 mJy at 1.4 GHz; Condon et al. 1998). The radio spectrum is steep with a spectral index (325 MHz to 8 GHz) of $\alpha = -0.73$ ($S_\nu \propto \nu^\alpha$).

A search of the ROSAT public archive revealed that FIRST J1643+3156 appears serendipitously in a PSPC observation. The source is clearly detected (5 ksec effective exposure time), but lies near a support rib and outside the inner support ring (offaxis angle=31.6$'$) where the point response function is degraded. We extraced the source using a circular aperture of 2.5$'$, subtracted an appropriate background, and corrected for vignetting. We used XSPEC to fit the background subtracted spectrum with an absorbed powerlaw using a fixed value of N_H=2.2$\times$10^{20} cm^{-2} (Dickey & Lockman 1990). The fit proved adequate (χ^2_ν = 1.05, 13 dof) and yielded a photon index of 2.7 $\pm$ 0.2 and a 0.1-2.4 keV flux of 1.1$\times$10^{-12} erg s^{-1} cm^{-2} (L_x = 1.1$\times$10^{45} ergs s^{-1}).

Table 1 summarizes the positions and separable properties of the FIRST J1643+3156 system. A correction for the low Galactic reddening of A_B = 0.07 has not been applied. Given the semi-arbitrary absolute magnitude that separates Seyfert galaxies from quasars ($M_B = -23$, for $H_0 = 50$, $q_0 = 0$, Veron-Cetty & Veron 1998), A is a quasar and B is a Seyfert 1 galaxy. Below, we will continue to refer to both components as quasars.

3. DISCUSSION

We have discovered a binary quasar system. We can rule out the lensing hypothesis for FIRST J1643+3156A,B because while the quasars have similar optical magnitudes, one is radio-loud while the other is radio-quiet. Additionally, their optical colors and spectra differ significantly, with the brighter quasar possessing a stronger narrow-line spectrum and stronger Balmer emission lines relative to the continuum. Finally, we see no evidence for a lensing galaxy in our K' image; our detection limit is $K' \approx 18$ (coincident with the quasars), while the expected magnitude for a lensing galaxy causing a 2$''$.3 separation is $\sim$14-15 magnitude (e.g., Keeton et al. 1997; Jackson et al. 1998).

The color difference of the two quasars appears to be primarily the result of a host galaxy in B. The spectral division in the bottom panel of Fig. 1 shows an approximately constant A/B $\approx$ 2.1 in the blue, which drops to about 1.5 at longer wavelengths. In the K' band the ratio has dropped further to 1.3. The colors and shape of the spectral division are consistent with a Balmer jump from a stellar contribution to the spectrum of B, which we might expect to see given its Seyfert-level luminosity.

Figure 3 shows Ca II and high-order Balmer absorption lines characteristic of a young (<0.5 Gyr) stellar population (at the system redshift and not intervening). If the AGN in A and B have the same optical-infrared spectral energy distribution, then the stellar light of B contributes $\geq$ 30% of the flux at R and $\geq$ 60% of the flux at K'. We can estimate the spectrum of the host galaxy of quasar B under the above assumption. We clipped the narrow emission lines from the quasar A spectrum and then scaled it so that the flux in Mg II matched that of quasar B. Subtracting this spectrum from that of quasar B results in a recognizable galaxy spectrum (Fig. 3, bottom) consistent with that of a starburst galaxy (dotted line). The starburst in the quasar B host galaxy may have been triggered by the interaction with quasar A.

Of additional interest is that the radio emission associated with quasar A is compact ($\theta \sim 1.4'' = 6.2h^{-1}$ kpc) and has a steep spectrum ($\alpha = -0.73$), indicating that A is a compact steep spectrum (CSS) source. Radio-loud quasars are also X-ray loud compared to radio-quiet quasars, and the more luminous quasar A very likely emits the majority of the observed X-rays. Quasar A has radio, optical (especially the strong narrow-emission line spectrum), and X-ray properties consistent with those of other CSS sources (as reviewed by O'Dea 1998). One hypothesis is that CSS sources are "frustrated" radio jets, unable to drill through a surrounding dense medium. The other leading hypothesis is that CSS sources are the progeni-

[1]DIMSUM is the Deep Infrared Mosaicing Software package, developed by P. Eisenhardt, M. Dickinson, A. Stanford, and J. Ward, which is available as a contributed package in IRAF.

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

tors of large-scale classical double sources. Disturbed morphologies or interactions, including tidal tails, are ubiquitous among the host galaxies of CSS sources (Gelderman 1994, 1996), and perhaps such an interaction (as in the present example of this binary quasar) is required to ignite a powerful radio-loud AGN.

There is a small difference in the quasars' redshifts. A cross-correlation analysis indicates that A is redshifted relative to B by 282±98 km s^{-1}. The narrow-line peak wavelengths suggest a smaller value: [O III] λ5007 and [O II] λ3727 in A are redshifted by 80±10 km s^{-1} relative to the same lines in B. Our spectrum of A was obtained with a $1''$ east-west slit, close to the radio position angle, and shows that the [O III] λ5007 emission is spatially extended by $\approx 5''$ (after subtracting in quadrature the continuum extent). CSS sources as a class display this "alignment effect" where optical and radio emission have coincident position angles and related features (Gelderman 1994, 1996; De Vries et al 1997). The aligned emission in CSS sources appears to be dominated by emission lines (De Vries et al. 1998), which are very luminous in these objects, and may be generated by shock-ionized gas from the interaction of the radio jet with the gaseous environment of the host galaxy (Bicknell et al. 1997).

Assuming that our binary is bound and isolated, we can calculate a limit to the total system mass:

$$M_A + M_B \geq \frac{Rv^2}{2G} \qquad (1)$$

M_A and M_B are the masses of the quasars, R is their projected separation (10.1 h^{-1} kiloparsecs), v is their radial velocity difference, and G is the Gravitational constant. The total mass is greater than $7.7\times10^9 h^{-1} M_\odot$ for a velocity difference of 80 km s^{-1}, which is a very modest limit.

Kochanek, Falco, & Muñoz (1998) review the known quasar pairs with the purpose of discriminating between gravitationally lensed and binary systems. They find three quasar pairs with greatly discrepant optical and radio flux ratios (O^2R pairs): the aforementioned PKS 1145–071 (Djorgovski et al. 1987), MGC 2214+3550 (Muñoz et al. 1998), and Q 1343+2640 (Crampton et al. 1988). FIRST J1643+3156 brings the total to four known O^2R binary quasar systems.

The properties of FIRST J1634+3156 are remarkably similar to those of MGC 2214+3550 ($z = 0.88, I = 18.8, 19.3$, sep. $= 3\farcs0$). The brighter quasar in MGC 2214+3550 is again a CSS radio source. Other similarities include: optical luminosities, optical A/B flux ratios, radio luminosities, radio spectra ($\alpha = -0.86$ for MGC 2214+3550), radio angular size, physical separation, radio position angle relative to the binary, and an alignment effect (based on a Hubble Space Telescope NICMOS H-band image of MGC 2214+3550, available from the CASTLe Survey web page, Kochanek et al. 1999). Some of these may be selection biases; still, given the small number of systems so far identified, the similarities suggest that there may be a small range of parameters for galaxy interactions that lead to radio-loud/radio-quiet binary systems.

4. CONCLUSIONS

We have identified a new binary quasar associated with the radio source FIRST J164311.3+315618. The system is binary and not lensed because one quasar is radio loud while the other is radio quiet, and there are other inconsistencies with the lensing hypothesis. The brighter quasar is a compact steep spectrum source with a strong narrow emission-line spectrum and extended [O III] λ5007 along the radio axis. The spectrum of the fainter quasar, formally a Seyfert 1 galaxy, has a significant stellar contribution from a young population as evidenced by high-order Balmer absorption lines. As the lowest redshift ($z = 0.586$) binary quasar known, FIRST J164311.3+315618A,B provides the best available laboratory for investigations of the binary quasar phenomenon, and for investigations of what conditions may lead to radio-loud activity as opposed to radio-quiet activity.

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TABLE 1
BINARY POSITIONS AND PROPERTIES

Component	R.A. (J2000)	Decl. (J2000)	z^{a}	E	$O-E$	K'	$S_{3.6_{cm}}$ (mJy)	$M_B{}^{b}$
A	16 43 11.33	+31 56 18.3	0.5867	18.5	−0.1	16.6	36.4	−23.3
B	16 43 11.38	+31 56 20.6	0.5862	19.0	0.2	17.0	0.4[c]	−22.8

[a]Calculated based solely on [O III] λ5007 wavelengths.

[b]Assuming $H_0 = 50, q_0 = 0$ and computed for direct comparison with Veron-Cetty & Veron (1998).

[c]4 σ detection.

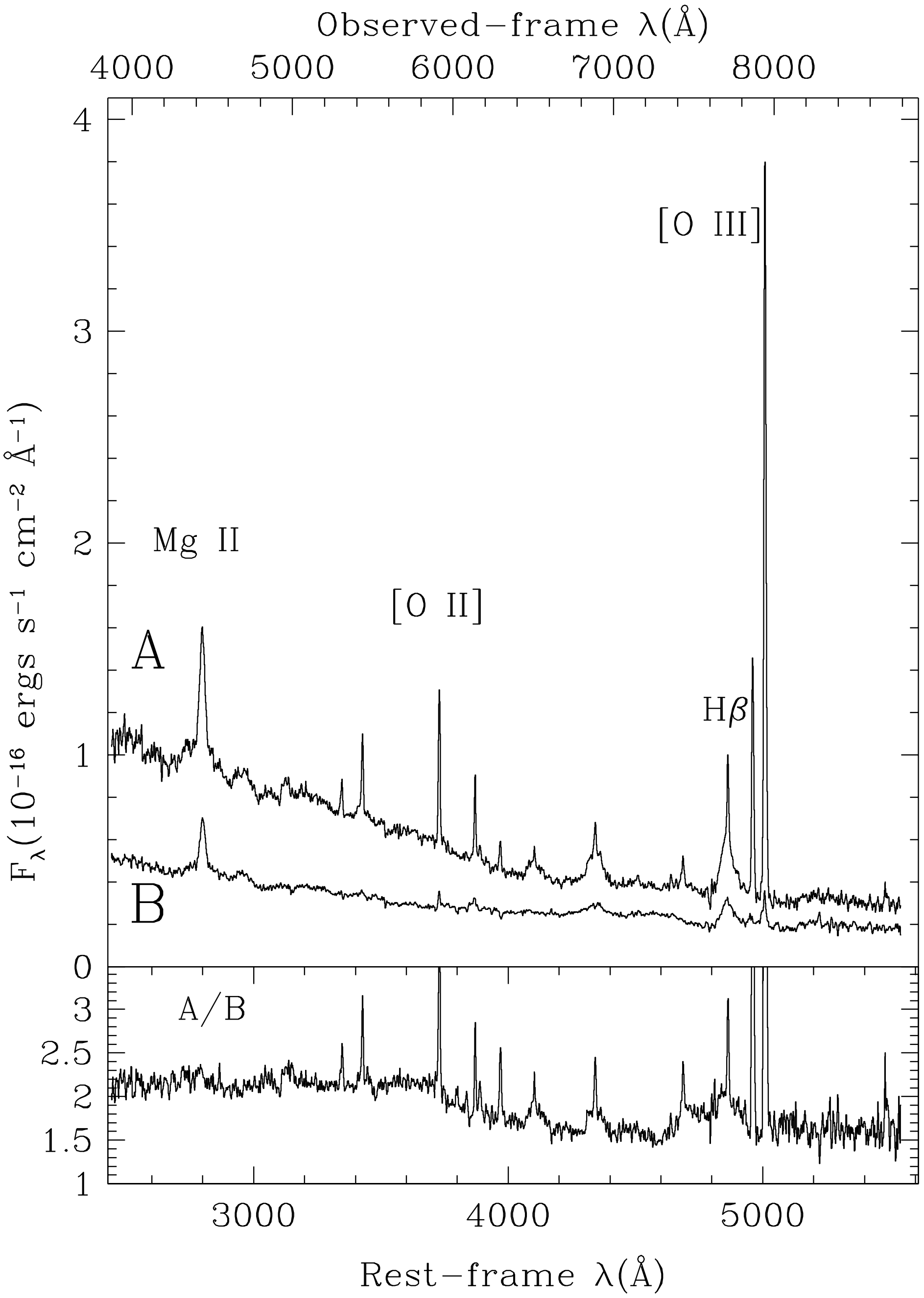

Fig. 1.— Upper panel: Keck II LRIS spectra of the binary component A (3 min. exposure) and B (10 minute exposure). The spectra have been boxcar smoothed by three pixels. The lower panel shows the ratio of A to B. Rest-frame wavelengths assume $z = 0.586$.

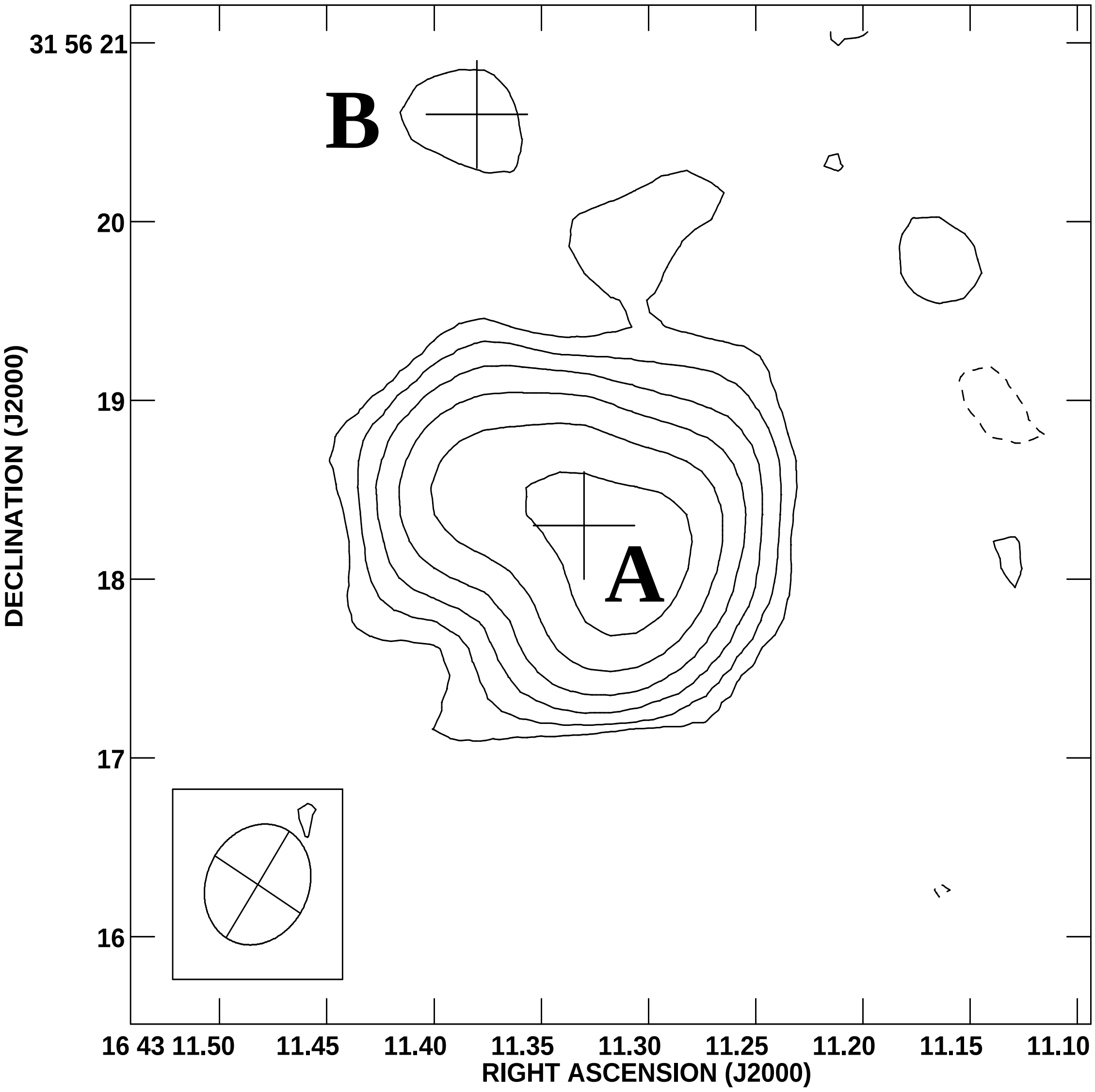

FIG. 2.— Total intensity 3.6 cm radio countour map of FIRST J1643+3156. Peak flux is 16 mJy and contour levels are at −0.25, 0.25, 0.5, 1, 2, 4, and 8 mJy. The integrated flux of Component A is 36 mJy and its largest angular size is 1.″4. The map RMS is 0.11 mJy and source B is detected at the ∼4σ level. The optical/infrared positions are marked and the size of the crosses indicate the formal astrometric uncertainty. The scale is 4.4h^{-1} kpc arcsec^{-1} for q_o=0.

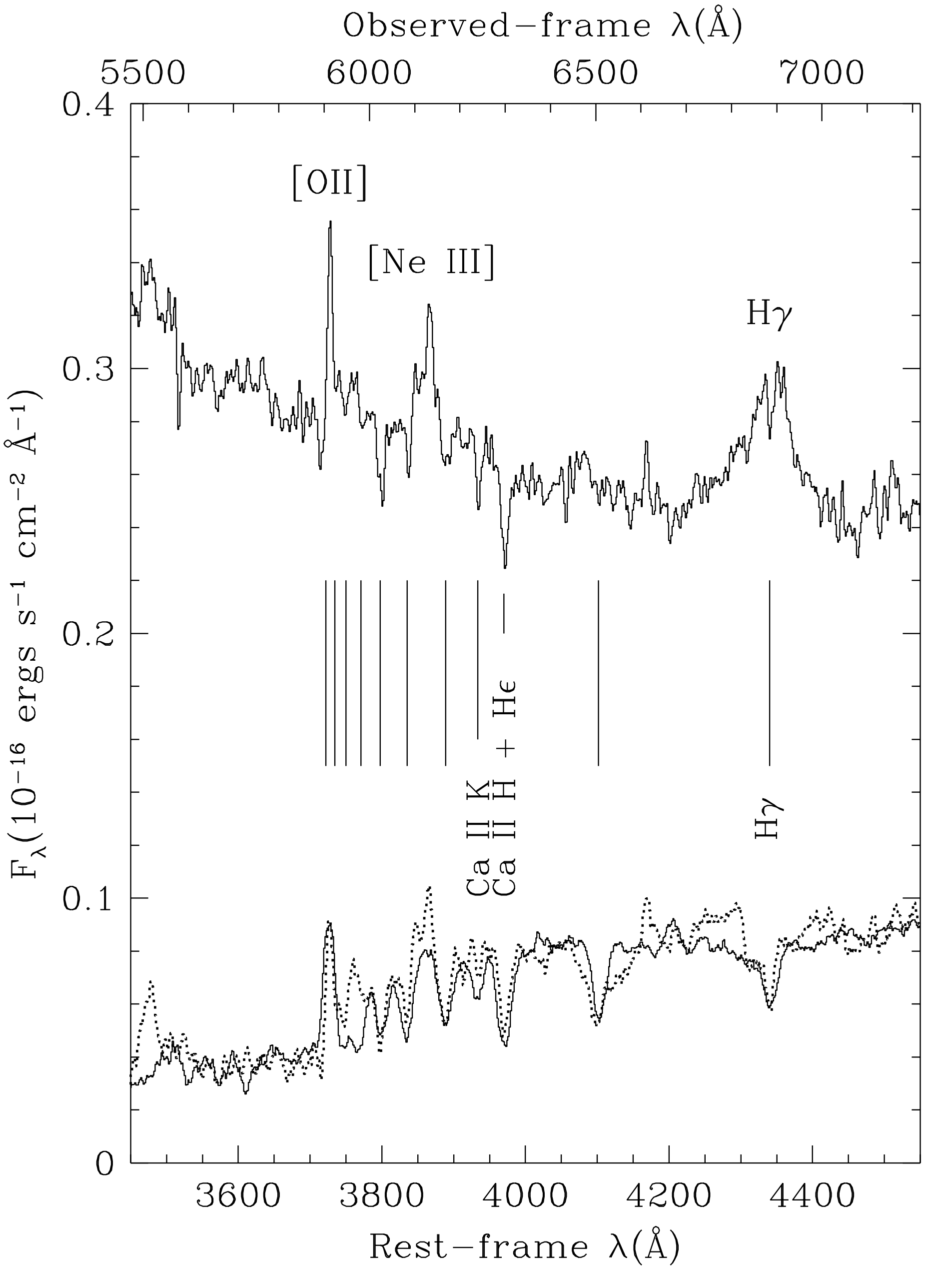

Fig. 3.— Top: The spectrum of quasar B, detail. Rest-frame wavelengths assume $z = 0.5862$. Stellar absorption features are marked where expected for the redshift, and include Ca II K lines and Balmer lines through H12. At the bottom is shown the difference spectrum representative of the B host galaxy, as described in the text, and for comparison is a starburst galaxy FIRST J103540.0+355124 (White et al. 1999) (dotted line).