Blazar Continuum Variability
ASP Conference Series, Vol. 110, 1996
H. R. Miller, J. R. Webb, and J. C. Noble, eds.

Powering the Broad Hα Line in BL Lacertae

Elizabeth Corbett, Andrew Robinson, James Hough, and Stuart Young

Dept. of Physical Sciences, University of Hertfordshire, College Lane, Hatfield, Herts. AL10 9AB, UK

David J. Axon

Affiliated to the Space Sciences Division of ESA, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218 (on leave from National Radio Astronomy Observatory, University of Manchester, Jodrell Bank, Macclesfield, Cheshire SK119DR, UK)

Abstract. We present high quality optical spectropolarimetry of BL Lacertae confirming the presence of a broad Hα emission line which is comparable in width (FWHM≈ $4000\,\mathrm{km\,s^{-1}}$) and luminosity ($L_{H\alpha} \sim 10^{41}\,\mathrm{erg\,s^{-1}}$) to those of Seyfert Type 1 nuclei. We tentatively conclude that this feature must have increased in luminosity by a factor ~ 4 since earlier spectroscopic observations. The beamed synchrotron continuum associated with the radio source can account for the observed equivalent width, but the fact that the line has not previously been detected suggests either a sudden injection of cold gas into the radiation field, or the strengthening of an additional ionizing radiation source. Using a simple model for the illumination of the broad line region (BLR) we show that the Hα emission could be powered by thermal radiation from an accretion disk, without significantly affecting the shape or polarisation of the optical continuum.

1. Introduction

Among blazars a distinction is generally drawn between optically violent variable or high polarization quasars (which for convenience we hereafter refer to collectively as OVV quasars) and BL Lacertae objects (BLOs), which lack the characteristic broad emission lines of quasars and whose optical-IR continuum appears to be pure synchrotron emission. This simple empirical distinction has, however, become somewhat blurred by the detection of broad emission lines in the spectra of several sources which were originally classified as BLOs (e.g., OJ287, Sitko & Junkkarinen 1985; Mkn 501, Moles et al. 1987; 1308+326, Stickel et al. 1993; and PKS 0521–36, Ulrich 1981). While it is possible that some of these cases can be attributed to mis-classifications, the recent discovery of a broad Hα line in the *class prototype*, BL Lacertae itself (Vermeulen et al. 1995), now demands a revision of the conventional picture of these objects and their relationship with quasars. In particular it raises the question of whether the designation "BL Lacertae Object" reflects genuinely different physical properties or, for example, describes an evolutionary state, as might be the case if the broad-line emission is episodic.

Here we present optical spectropolarimetry of BL Lacertae obtained two weeks after Vermeulen et al.'s (1995) observations and discuss the merits of alternative models in which the line emission is powered, respectively, by beamed synchrotron emission from the relativistic jet and by thermal emission from an accretion disk. This work is described in more detail by Corbett et al. (1996).

2. Observations and analysis

Spectropolarimetric observations of the Hα region of BL Lacertae were made with the 4.2-m William Herschel Telescope using the ISIS dual beam spectrograph (giving a dispersion of 3Å/pixel) on the nights of June 4–5 and June 6–7. The total exposure time in each case was 2400 s. The strength of the broad Hα line does not differ significantly between the two data sets and hence for brevity measurements made from the average spectrum are given here. After correcting for atmospheric absorption and line-of-sight reddening (assuming E(B–V)=0.3), the Hα+[NII] feature was decomposed by fitting gaussians (Fig. 1). The broad Hα component has a FWHM $\approx 4000 \pm 200\,\mathrm{km\,s^{-1}}$ and an equivalent width $W_{\mathrm{H}\alpha} \approx 5.5 \pm 0.3$Å. Its integrated flux is $3.0 \pm 0.2 \times 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-1}}$, corresponding to a luminosity of $1.5 \times 10^{41} h^{-2}\,\mathrm{erg\,s^{-1}}$ where $h = H_0/100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The H$\alpha$ line is very similar in luminosity and FWHM to that of the classical Type 1 Seyfert NGC4151. The linear polarization varies only slightly over the spectrum and has an average of 4.39± 0.04%, among the lowest recorded values in this wavelength range (Sitko, Schmidt, & Stein 1985). Simultaneous photometric observations show that during the period 4–9 June BL Lacertae underwent night-to-night variations by 0.1 magnitude within the range $15.8 \leq V \leq 15.5$. These measurements place BL Lacertae at the lower end of its typical variability range ($14 \leq V \leq 16$; e.g., Carini et al. 1992), but also show that it was not exceptionally faint.

2.1. Should the line have been seen before?

One major question which will critically effect how we interpret this result is: has the broad Hα line appeared as a genuine new feature in the spectrum or has it always been present, having previously escaped detection? We estimate that the broad Hα would not have been discernable in our own data if the optical continuum had been significantly brighter ($\sim 1.5 - 2^m$) than it actually was during our observations. Nevertheless, BL Lacertae was not unsually faint and so if the broad line only becomes visible when the beamed optical continuum is weak, we would expect that it should have been detected in earlier spectra if it was indeed present at a luminosity comparable with what we measured in June 1995. In fact, previous spectra of BL Lacertae, (e.g., Miller & Hawley 1977, Stickel et al. 1993) show no easily identifiable broad emission line features, even when the source had a similar V magnitude. We estimate that the broad Hα feature would have been undetectable in our own spectra if reduced to $\sim 25\%$ of its observed flux and therefore, taking its absence from earlier spectra at face value, we conclude that it must have increased in luminosity by a factor ~ 4.

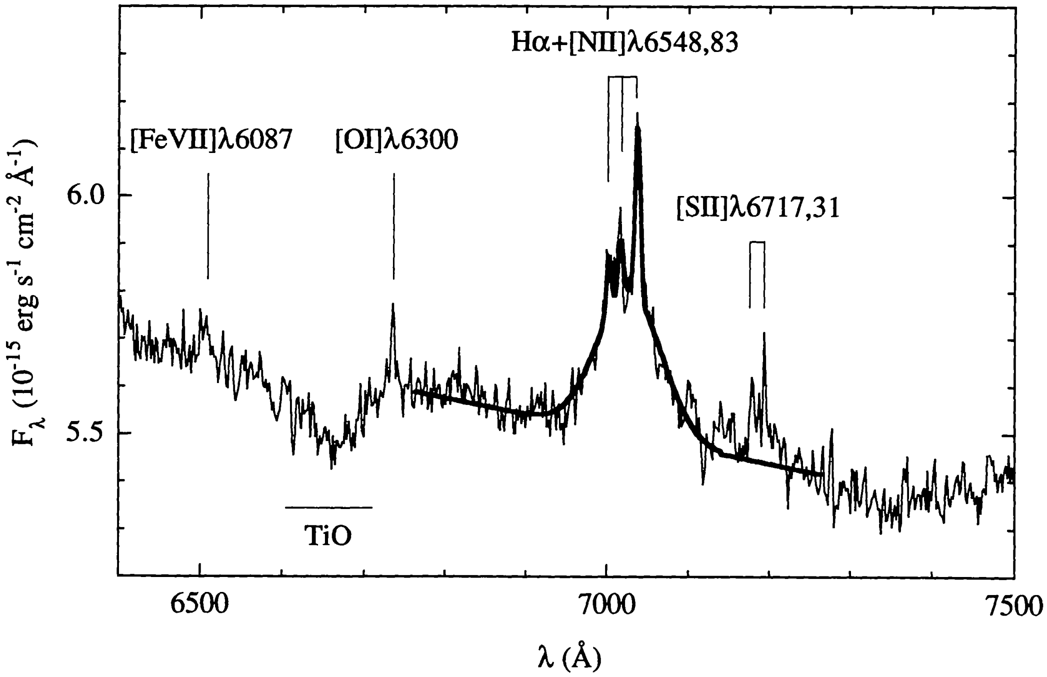

Figure 1. The emission line spectrum of BL Lacertae. Shown here is the average of the spectra obtained on the nights of 1995 June 4–5 and 6–7. The thick lines show the multi-Gaussian fits to the broad Hα+[NII] blend.

2.2. Powering the broad emission line

The broad emission lines exhibited by AGN are believed to arise from photoionization of cool, dense, rapidly moving gas clouds (the broad line region, or BLR) by the central continuum source. The inferred increase in the luminosity of the Hα line in BL Lacertae could therefore be attributed either to an increase in the BLR covering factor, or assuming that enough cool gas is already present, to an increase in the level of illumination by the ionizing continuum. Two main continuum sources are believed to operate in radio-loud quasars: a relativistic jet emitting Doppler-boosted synchrotron radiation, and the hot inner regions of the black-hole accretion disk, emitting thermal radiation in the EUV.

The pure synchrotron illumination model We first consider whether the broad Hα line in BL Lacertae can be explained in terms of illumination of the BLR by the Doppler-boosted synchrotron continuum alone. We model the continuum source as two identical relativistic jets pointing in opposite directions along the same axis. The synchrotron continuum emitted by the jets is represented by the power law $f_\nu \propto \nu^{-\alpha}$ and is Doppler-boosted by the factor $D^{3+\alpha}$, where $D = [\gamma(1-\beta\cos i)]^{-1}$, β is the jet velocity in units of c, i the jet inclination to the line of sight and γ the Lorentz factor. For the spectral index we take $\alpha = 2$ (e.g., Bregman et al. 1990). The observed superluminal motion of the radio source (Mutel et al. 1990) implies that $i \leq 34°$ and $\gamma \geq 3.4$. The BLR is modelled as a uniform distribution of clouds arranged, with a covering factor $C = 0.1$, in a thin spherical shell centerd on the continuum source. The Hα

emissivity is given by $\epsilon_s(\mathrm{H}\alpha) \propto CF(\theta)\max[1,\delta]$, where $F(\theta)$ is the photon flux impinging on the shell at an angle θ from the jet axis and $\delta(\propto 1/F(\theta))$ is the ratio of the column density of the clouds to the Strömgren column.

If the BLR is everywhere radiation bounded, i.e., $\delta \geq 1$, for all θ, the measured equivalent width of the broad Hα line can easily be obtained for $\gamma \approx 4$ and $i \approx 20°$. However as both the line luminosity and the underlying continuum are directly proportional to the intrinsic synchrotron power, $W_{\mathrm{H}\alpha}$ would be independent of the continuum luminosity. It is unlikely that a broad Hα line of *constant* equivalent width would have escaped detection in all previous observations so the appearance of the broad Hα line cannot be explained simply by an increase in the beam power with γ fixed.

An alternative possibility is that γ varies, producing changes in D. If the BLR remains radiation bounded, the line luminosity is an increasing function of γ due to enhanced Doppler-boosting of the continuum. On the other hand, the beam becomes narrower so the *observed* continuum flux is initially boosted but then drops rapidly when the value of γ is such that the effective opening angle excludes the line of sight. As a result, relatively small changes in the bulk velocity of material moving along the jet can cause large variations in $W_{\mathrm{H}\alpha}$ with, typically, a decrease in the continuum by $\sim 0.1^m$ corresponding to a doubling of $W_{\mathrm{H}\alpha}$. This is difficult to reconcile with the lack of an earlier detection since we would expect a strong line to appear when BL Lacertae is in a low state.

If the BLR is matter bounded near the beaming axis (i.e., $\delta < 1$ for $\theta < \gamma^{-1}$), some ionizing photons pass through the BLR without being absorbed and somewhat larger values of $\gamma(\approx 4.5)$ and $i(\approx 23°)$ are needed to obtain the observed $W_{\mathrm{H}\alpha}$. For BLR properties typical of Seyferts, these values remain within the limits implied by the superluminal motion but we would still expect to see higher $W_{\mathrm{H}\alpha}$ when the continuum is faint.

Hence although the observed $W_{\mathrm{H}\alpha}$ can be explained by illumination of the BLR by the beamed synchrotron continuum, this model also predicts that it increases or at least remains constant as the observed continuum fades. It follows that the line should have been at least as strong in previous spectra obtained when BL Lacertae was as faint as it was in June 1995. If the broad Hα line is indeed a new feature in the spectrum as we have argued, then its luminosity be cannot be directly related to the intensity of the synchrotron beam and must be attributed either to a sudden injection of cool dense gas into the radiation field or to the strengthening of a second ionizing source which does not contribute substantially to the optical continuum.

An additional continuum source—the accretion disk In Seyfert 1 nuclei and quasars the ubiquitous flattening of the optical continuum shortwards of 4000Å (known as the "big blue bump") is widely attributed to thermal radiation from the accretion disk and is invariably associated with strong emission lines. Although the Doppler-boosted synchrotron emission dominates over much of the IR–optical range in OVV quasars, signatures of the big blue bump are often seen at shorter wavelengths (e.g., 3C345, Smith et al. 1986). An accretion disk is therefore an obvious candidate for an additional ionizing continuum source in BL Lacertae. To investigate this possiblity we have altered our model to include a simple isotropic accretion disk continuum of the form $f_\nu \propto \nu^{1/3}e^{-h\nu/kT}$, where we take $T = 1.5 \times 10^5$, a value comparable to those inferred for Seyfert 1 nuclei.

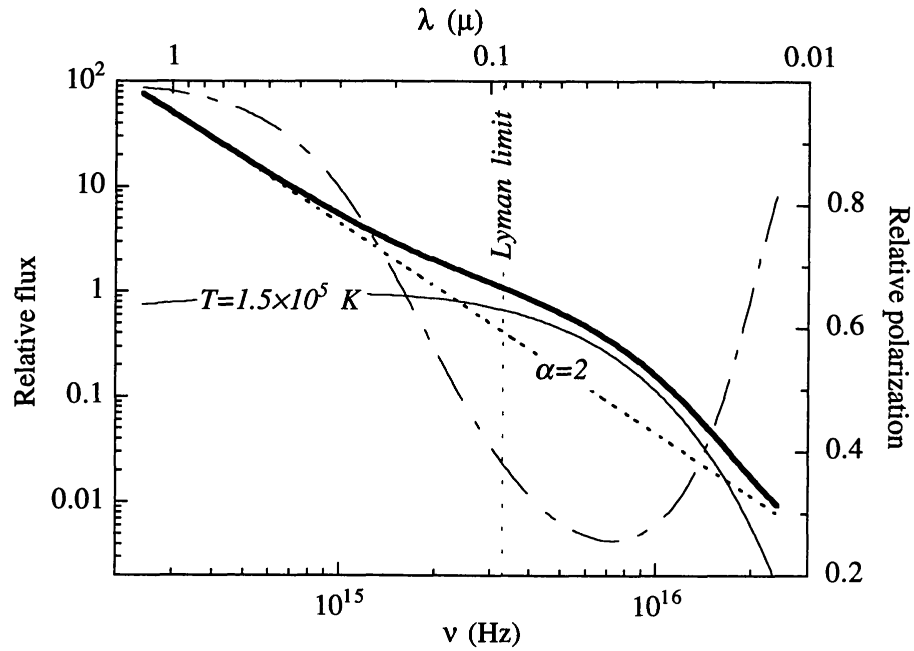

Figure 2. A model in which the continuum spectrum (thick line) has contributions from both a synchrotron beam (dotted line) and a hot accretion disk (thin line), with the beam intensity 25× that of the disk emission at Hα. The dot-dashed line shows the depolarization which would result from dilution of the pure synchrotron continuum (having unit intrinsic polarization) if the disk emission is unpolarized.

The observed continuum flux density is now the sum of the synchrotron and the disk continua but, for simplicity, we assume that BLR is illuminated only by the latter so that for a given covering factor, the Hα line luminosity is determined solely by the power of the thermal source (we might imagine, for instance, that the synchrotron beam shines through a hole in the BLR).

For the combined continuum the observed value of $W_{\mathrm{H}\alpha}$ is obtained when the flux density of the synchrotron continuum $\approx 25\times$ that of the thermal continuum at the wavelength of Hα. This result is effectively independent of γ and i but is sensitive to the disk temperature; as T increases, relatively more ionizing photons are produced and the observed $W_{\mathrm{H}\alpha}$ is achieved with an even smaller thermal contribution to the continuum under Hα.

A thermal continuum sufficiently powerful to produce the observed broad Hα emission by photoionization could therefore be accommodated within the optical spectrum of BL Lacertae without easily detectable modifications to the spectral shape or polarisation, at least for wavelengths > 4000Å (Fig. 2). The line emission would be weakly related to the overall optical continuum brightness which would still be dominated by Doppler-boosted synchrotron emission. Changes in the Hα luminosity could be driven by flares in the accretion disk which are unlikely to be strongly correlated with the variability of the synchrotron beam, so the broad Hα line would not inevitably appear as the optical continuum fades.

3. Conclusion

BL Lacertae is now known to exhibit broad Balmer lines in its spectrum, and our observations show that while the broad Hα line has a relatively small equivalent width, it is comparable in luminosity and width to those of Seyfert 1 nuclei. Given that this feature is apparently absent in earlier spectra obtained when the source had a similar V magnitude, we infer that the line luminosity has increased by a factor ~ 4. The observed equivalent width can be explained if the BLR is illuminated by a Doppler-boosted synchrotron continuum from relativistic jets, but if we take the lack of previous detections of the line at face value, its subsequent appearance is difficult to explain and suggests an injection of gas into the radiation field or the strengthening of an additional ionizing continuum source. A thermal accretion disk can account for the observed equivalent width without easily detectable consequences for either the polarisation properties or the slope of the optical continuum. If the latter explanation is correct, it follows from unified schemes relating BLOs to a parent population of FR I radio galaxies (e.g., Browne 1983) that the latter must also harbour Seyfert-like nuclei including broad emission line regions and accretion disks.

Acknowledgments. We thank R. D. Jeffries and M. R. Thurston for providing us with their photometric data. EAC acknowledges a PPARC reseach studentship and AR thanks the Royal Society for financial support.

References

Bregman, J. D., et al. 1990, ApJ, 352, 574

Browne, I. 1983, MNRAS, 214, 23p

Carini, M., Miller, H., Noble, J., & Goodrich, B. 1992, AJ, 104,15

Corbett, E., Robinson, A., Axon, D., Hough J., Jeffries, R., Thurston, M., & Young, S. 1996, MNRAS, submitted

Miller, J., & Hawley, S. 1977, ApJ, 212, 47

Moles, M., Masegosa, J., & del Olmo, A. 1987, AJ, 94, 1143

Mutel, R. L., Phillips, R. B., Su, B., & Bucciferro, R. R. 1990, ApJ, 352, 81

Sitko, M., & Junkkarinen, V. 1985, PASP, 97, 1158

Sitko, M., Schmidt, G., & Stein, W. 1985, ApJS, 59,323

Smith, P., Balonek, T., Heckert, P., & Elston, R. 1986, ApJ, 305, 484

Stickel, M., Freidel, J., & Kühr, H. 1993, A&AS, 98, 393

Ulrich, M. 1981, A&A, 103, L1

Vermeulen, R. C., Ogle, P. M., Tran, H. D., Browne, I. W. A., Cohen, M. H., Readhead, A. C. S., Taylor, G. B., & Goodrich, R. W. 1995, ApJ, 452, 5