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Monitoring the Hα Line in BL Lacertae - Evidence for an Accretion Disk?

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Abstract. We present new spectroscopic observations of the recently discovered broad Hα line in BL Lacertae. These data, obtained over a period of 30 months, indicate that the line equivalent width is anti-correlated with the continuum flux, implying that the broad line emission is not powered primarily by synchrotron emission from the relativistic jet. The most probable explanation is that the broad line region in BL Lacertae is photoionized by continuum emission from an accretion disk which at optical wavelengths is dominated by the Doppler beamed synchrotron continuum.

1. Introduction

Although BL Lac objects share many continuum properties with optically violent variables (OVVs) or highly polarized (HP) quasars, they are conventionally distinguished from quasars by their lack of strong emission lines. This distinction has become somewhat blurred, however, by the detection of broad emission lines in several sources which were originally classified as BL Lac objects. Recently Vermeulen et al. (1995) discovered broad emission lines in BL Lacertae, the prototype BL Lac object, at the redshifted wavelengths of Hα and Hβ. The broad Hα line has a small equivalent width (~6Å) but its luminosity ($L_{H\alpha} \sim 10^{41}$erg s^{-1}) and full width half maximum (FWHM ~ 3700 km s^{-1}) are comparable to those of Seyfert type 1 galaxies such NGC 4151 (Corbett et al. 1996; C96 hereafter).

Assuming that the broad-line emitting gas in BL Lacertae is photoionized, the only apparent ionization source is beamed synchrotron continuum emitted by the jet. The broad-line region (BLR) would then be illuminated by a highly anisotropic radiation field and C96 showed that the observed Hα equivalent width is consistent with this for jet Lorentz factors and viewing angles within the limits implied by the observed superluminal motion of the radio source

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(Mutel et al. 1990). Nevertheless, it can equally well be explained by thermal radiation from an accretion disk without observable consequences for the optical continuum, e.g. a spectral flattening or depolarization of the observed continuum towards the blue. If this is the case, it would be reasonable to suppose that BL Lacertae, and its class, are intrinsically similar to quasars in that both a BLR and an EUV-emitting accretion disk are present in their nuclei.

In principal, we can distinguish between these two continuum sources from the way in which the Hα equivalent width, $W_{\mathrm{H}\alpha}$, varies with the optical continuum brightness. If an accretion disk is the primary source of photoionizing radiation for the BLR, the line emission will be independent of variations in the observed optical continuum, since this is dominated by synchrotron emission, and $W_{\mathrm{H}\alpha}$ will therefore be inversely proportional to the continuum brightness. On the other hand, we expect $W_{\mathrm{H}\alpha}$ to remain constant or decrease slowly as the optical continuum brightens, if the broad-line emission is powered by radiation from the same source, i.e. the synchrotron beam. Here we present a series of spectroscopic observations of the Hα line in BL Lacertae, obtained over a period of 30 months, and use these data to determine the nature of the relationship between the line equivalent width and the optical continuum flux.

2. Observations and Results

Observations of the Hα region of BL Lacertae were obtained with the 4.2m William Herschel Telescope at the Observatorio del Roque de los Muchachos on La Palma. The ISIS dual beam spectrograph was used with a 1″ slit in all observations. In total, eight spectra were acquired at irregular intervals during a period of 30 months (Table 1). Each spectrum has a wavelength range of 1500Å at a dispersion of 1.5 Å/pixel and when several spectra were obtained during one or two (consecutive) nights they have been combined to form an average spectrum.

The spectra were flux calibrated in the usual way using observations of spectrophotometric standard stars. On a few occasions (1995 June 4, 1997 November 30 and 1997 December 7) we were able to obtain near simultaneous CCD photometry of BL Lacertae in the V band and these measurements were used to improve the flux calibration. On 1997 November 14 a wide slit observation of a reference star within 2 arcsec of BL Lacertae was obtained and its known R magnitude used to estimate the flux calibration correction. With the exception of the observations obtained on 1997 November 30, which were affected by cloud, the corrections applied were approximately 25% of the measured fluxes and we estimate that the error in the corrected fluxes measured from these spectra is 10% (the accuracy of the photometry). We believe that the flux measurement errors for the remaining 4 observations do not exceed the 25% corrections applied to the spectra for which we have photometric data.

The broad Hα line was clearly detected in all of our spectra except that obtained from the observations of 1997 June 27 and 28, when BL Lacertae was particularly bright. At this epoch the continuum flux was higher by a factor >2 than it was in its next brightest state (1997 December 7) and a factor >5 higher than it was in the faintest state we observed (1995 July 7). In subsequent observations obtained in 1997 November and December, after the source had faded, broad Hα was again detected at a strength comparable to that seen in the observations prior to 1997 June.

Prior to measuring the line and continuum fluxes from the spectra we applied corrections for atmospheric absorption, galactic extinction (using a value $E(B-V)$ ~0.3) and contamination by starlight as described in C96. The Hα+[NII] feature was decomposed by fitting gaussians representing, respectively, the broad wings and narrow core of Hα and the [NII]λ 6548,83 doublet. The continuum flux at 6563Å (F_{6563}) and the flux ($F_{H\alpha}$), equivalent width ($W_{H\alpha}$) and FWHM of the broad Hα line are listed in Table 1.

The simulations described in C96 suggest that the minimum detectable line equivalent width is 1-2Å in data of comparable quality to those obtained on 1997 June 27 and 28. We therefore set a conservative upper limit of 2Å on the equivalent width of the broad Hα feature at this epoch.

Table 1. Continuum flux and broad Hα line properties

Date	Total Exposure (s)	Corrected data $F^{a,b}_{6563}$ (Å^{-1})	$F^{a,b}_{H\alpha}$	$W^{b}_{H\alpha}$ (Å)	FWHM (km s^{-1})
1995 Jun 4[c]	2400	3.9±0.4	22.9±5.3	5.9±1.4	4020±450
1995 Jul 7	1200	3.7±0.9	26.1±7.4	7.0±1.2	4000±300
1995 Aug 24	2400	7.3±1.5	48±12.9	6.6±0.9	4050±220
1996 Aug 18	1200	7.7±1.9	26.6±7.1	3.4±0.5	2580±160
1997 Jun 27	2700	25.9±6.5	–	<2.0	–
1997 Nov 14[c]	3600	4.4±0.4	28.6±5.4	6.5±1.2	5050±490
1997 Nov 30[c,d]	3600	7.4±.7	28.6±4.6	3.9±0.6	4530±390
1997 Dec 7[1]	3600	10.8±1.1	17.1±2.6	1.6±0.2	2030±150

[a]In units of 10^{-15} erg cm^{-2} s^{-1}

[b]Corrected for extinction and host galaxy

[c]denotes observations for which additional flux calibration data was obtained

[d]an observation affected by clouds.

The variation of $W_{H\alpha}$ with the local continuum flux is shown for the corrected data in Fig. 1. It is clear that $W_{H\alpha}$ is anti-correlated with the continuum flux. While the continuum flux varied by more than a factor of 5 between the highest and lowest states sampled by our observations, 6 out of 7 measurements place the line flux at between 2.2 and 2.9×10^{-14} erg cm^{-2}s^{-1} (the 1995 August 24 measurement is not significantly different at the 2σ level); constant to within the uncertainties (Table 1). The remaining line flux measurement (1997 December 7) is much less than the mean and its formal uncertainty suggests that this is significant. However, the continuum brightness in this observation was the second highest we recorded and we believe that our fitting procedure may have significantly underestimated the flux in the broad line wings which are largely swamped by the continuum. Therefore, although the largest change in line flux that can be admitted by our measurements is approximately 50%, we believe that any changes that have occurred are probably somewhat smaller and indeed there is no compelling evidence in our data that the broad Hα flux has undergone any significant variations.

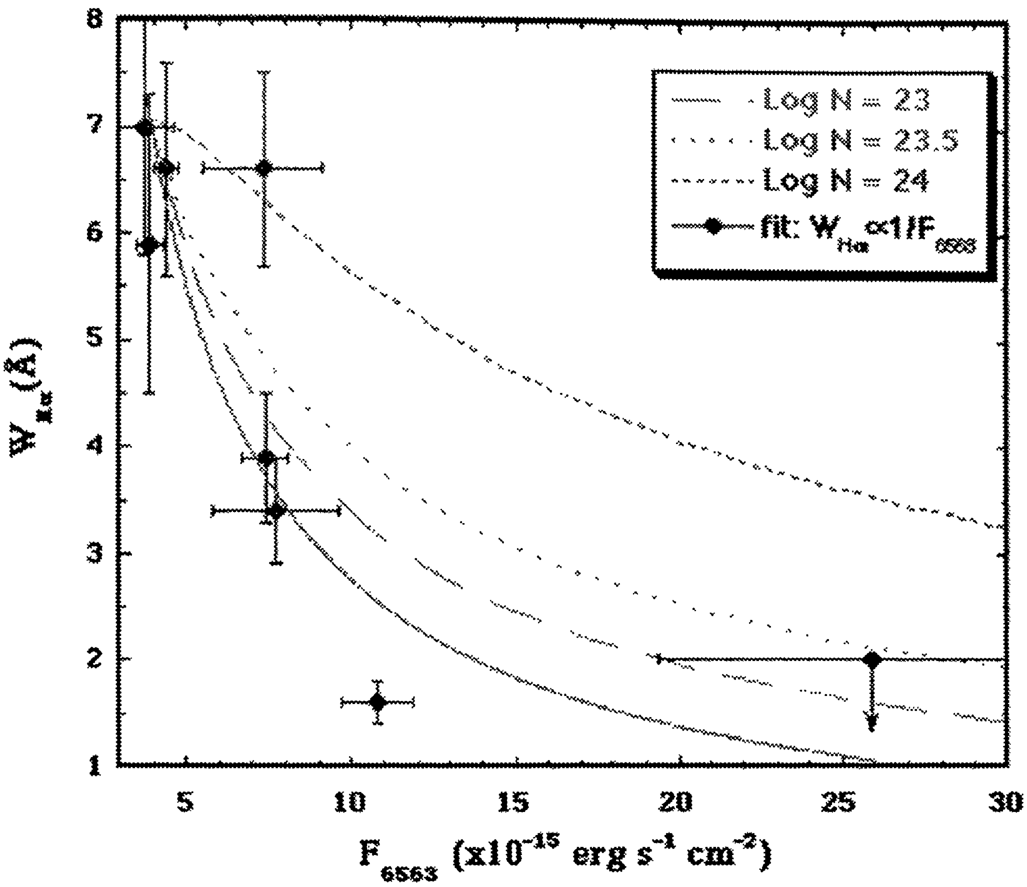

Figure 1. Plot showing the variation of $W_{\mathrm{H}\alpha}$ with the continuum flux under the line for the data after correction for galactic reddening and the host galaxy contribution. The equivalent width for the 27&28 June 1997 is shown as an upper limit. The solid line represents the best $\propto 1/x$ fit to the data and the dotted lines represent the expected behavior of a partially matter-bounded BLR photoionized by synchrotron emission from the jet.

3. Discussion

In C96 we found that the observed value of $W_{H\alpha}$ could be explained in terms of photoionization of the BLR by the beamed synchrotron continuum alone for jet parameters consistent with the observed superluminal motion of the radio source. Since studies of blazar variability reveal that the UV and optical continua vary together and only small delays ($\sim$ 2 days) exist between flares at X-ray and optical wavelengths, the optical continuum (attributed to synchrotron emission) will vary with the same amplitude as the photoionizing flux with a negligible delay. If the BLR is ionization-bounded, therefore, the line luminosity in this model will be approximately proportional to the the optical continuum and variations in the latter will be closely followed by variations in the Hα luminosity. In this case, we expect that the line flux should vary with the optical continuum, while $W_{H\alpha}$ remains roughly constant. This behavior is clearly not observed in BL Lacertae (Fig. 1).

It is possible, however, that the BLR is partially matter-bounded. In this case, as the continuum flux increases the BLR becomes fully ionized along the axis of the beam and hence the line luminosity no longer increases linearly with the continuum. Assuming the continuum to be a power law of the form $F \propto \nu^{-\alpha}$, where α, the spectral index, was taken to be 2 (typical of BL Lacertae; C96) we have calculated the expected relationship between $W_{H\alpha}$ and F_{6563} for several values of BLR column densities, N. A good fit to our data can only be achieved with $N \leq 10^{23}$cm^{-2} (Fig. 1) but Hα is emitted too inefficiently at this column density to obtain the observed $F_{H\alpha}$ with jet inclinations and velocities consistent with the observed superluminal motion.

In fact we detect no clear changes in the the line flux and $W_{H\alpha}$ is inversely correlated with the observed continuum. If the BLR is indeed photoionized, then it must be illuminated by a second, more isotropic source of ionizing photons which is weakly variable and sufficiently feeble at UV-optical wavelengths that it is overwhelmed by the beamed synchrotron emission. Thermal emission from the surface of a hot accretion disk would have these features. Such a situation was considered by C96, who modeled the optical continuum as a combination of beamed synchrotron emission from the jet and a constant contribution from a thermal accretion disk continuum represented by $F \propto \nu^{1/3} e^{h\nu/kT}$, where T is the characteristic temperature of the disk. The optical continuum is dominated by the synchrotron power-law but the disk emission peaks in the EUV (for $T >$ 10^5K) and is thus the dominant source of ionizing photons (Fig. 4). Variability in the optical, even with high amplitudes, will therefore have little effect on the line flux which is tied to the disk continuum. In the case of BL Lacertae, therefore, we expect $W_{H\alpha}$ to vary approximately inversely with the continuum flux. Our observations are consistent with this prediction. A function of the form $W_{H\alpha} = constant/F_\lambda$ produces a reasonably good fit to the data (Fig. 1).

Would an accretion disk continuum sufficiently strong to explain the observed $W_{H\alpha}$ produce an observable signature, such as a flattening of the continuum spectrum in the near UV? In the model discussed by C96 the characteristic temperature of the accretion disk was assumed to be $T = 1.5 \times 10^5$K, and the covering factor of the BLR to be 10%. With these assumptions we found that the accretion disk would contribute less than 6% of the observed optical continuum on 1995 July 7, when the source was at its faintest for our series of observations.

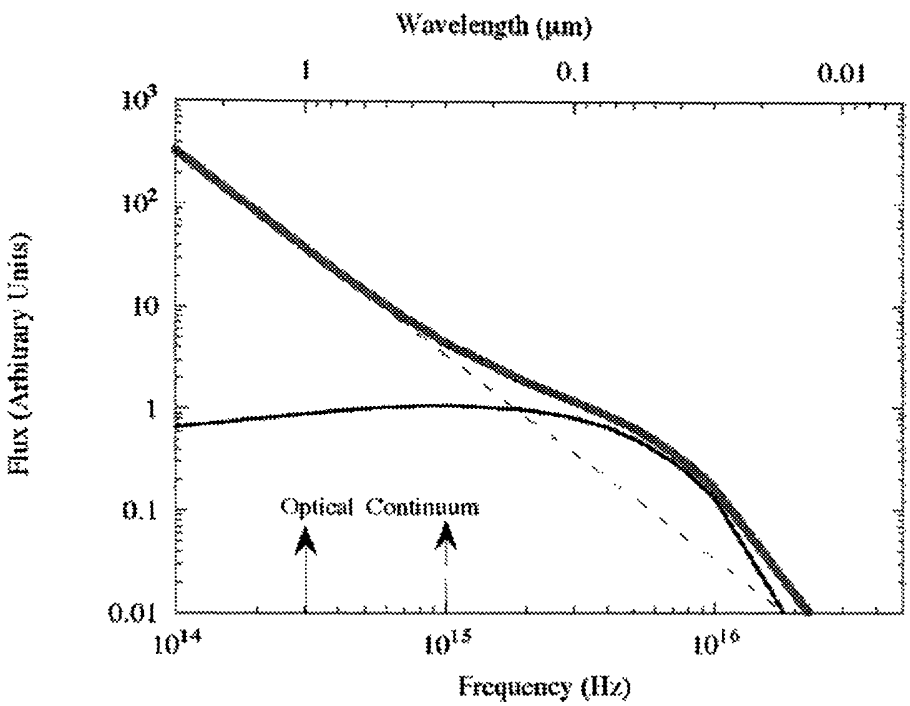

Figure 2. The predicted spectrum (thick line) for a model in which the continuum spectrum has contributions from both a synchrotron component (dotted line) and a hot accretion disk (thin line) which contributes 6% of the continuum emission at 6563Å.

In Fig. 2 we plot the the combined continuum spectrum inferred for a model in which the synchrotron power-law is characterized by α=2 and the disk continuum contributes 6% of the total flux at the wavelength of Hα. The slope of the combined continuum differs only slightly (α=1.75) from the pure synchrotron power-law in the range 8000Å- 4000Å; with significant flattening only becoming evident at shorter wavelengths. This model represents an upper limit since it corresponds to the smallest measured continuum flux and the largest values of $W_{\mathrm{H}\alpha}$. It is therefore unlikely that, even at low optical continuum brightness, an accretion disk component of this characteristic temperature would be detected in optical spectra. Cooler disks producing the same ionizing luminosity will make larger contributions to the optical continuum. We estimate that the characteristic disk temperature must be $T > 1.2 \times 10^5$K for the thermal component to remain undetected in the optical spectrum.

4. Conclusions

Measurements of the broad Hα emission in 8 spectra of BL Lacertae obtained over 30 months show that the line equivalent width, $W_{\mathrm{H}\alpha}$, is anti-correlated with the optical continuum flux. We conclude from this that the broad Hα line does not respond to changes in the power of the Doppler -beamed synchrotron emission which dominates the optical continuum. Similar results have been obtained from studies of the OVV quasars 3C 279 (Koratkar et al. 1998) and 3C 273 (Ulrich, Courvoisier & Wamsteker 1993); the line flux of Lyα remaining constant while the continuum flux varied by as much as a factor of 50.

The most likely explanation for the observed relationship between the continuum brightness and $W_{\mathrm{H}\alpha}$ in BL Lacertae is that the BLR is photoionized by emission from a second continuum source which is not directly observed in the optical band. An obvious candidate is a hot accretion disk. Hence these observations provide the first, albeit indirect, evidence of a Seyfert-like nucleus in the core of a BL Lac object. We estimate that disks with characteristic temperatures $T > 1.2 \times 10^5$K would be difficult to detect directly in optical spectra. In order to confirm the presence of such a source, observations in the far-UV or soft X-rays are required.

If these results can be extended to other BL Lac objects and their putative parent population, the FR I radio galaxies, then it seems that these objects are not fundamentally different from OVVs and FR II radio galaxies but also possess Seyfert-like nuclei including a broad emission line region and, as we have argued, an accretion disk.

References

Corbett, E. A., et al. 1996, MNRAS, 281, 737 (C96)

Koratkar, A. P., Pian, E., Urry, C. M., & Pesce, J. E. 1998, ApJ, 492, 173

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

Ulrich, M.-H., Courvoisier, T.J.-L., & Wamstreker, W. 1993, ApJ, 411, 125

Vermeulen, R. C., et al. 1995, ApJ, 452, L5