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UV and X-Ray Variability of 3C 390.3 [1]

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Abstract. We present the results of an analysis of the UV and X-ray variability of the broad-line radio galaxy 3C 390.3 over 15 years. The UV continuum of 3C 390.3 showed large variations with amplitudes of up to a factor of 10. The variations of C IV and Lyα are highly correlated with the UV continuum, and are delayed with respect to the continuum variations by 65–120 days with the red wing of both C IV and Lyα leading the blue wing, implying that the C IV and Lyα-emitting gas is infalling towards the center. The C IV/Lyα ratio is positively correlated with both the continuum flux and UV line strength. The overall UV/optical to X-ray spectrum can be described by a single power law with $\alpha_{uvx} = 0.90$. The behavior of C IV/Lyα variations might be related to this hard ionizing continuum in 3C 390.3.

1. Introduction

Emission-line reverberation has proven to be a powerful method to probe the distribution, as well as the physical and kinematic state, of the line-emitting gas surrounding AGN (see Peterson 1993 for a review). The method has been applied to a few bright Seyfert galaxies, and the results show: (1) the broad emission lines respond to the continuum variations very fast, and show a dependence on the ionization level of the ions, with the shortest response time for the highest ionization lines; and (2) the line-emitting gas is not dominated by radial motion.

3C 390.3 (1845+796) is a FR II radio galaxy at redshift $z = 0.0561$ and is a known superluminal source. Large-amplitude variations have been reported in the optical, UV, and X-ray bands (Veilleux & Zheng 1991; Clavel & Wamsteker 1987; Inda et al. 1994). The *IUE* observations of this object prior to 1986 have been discussed by Clavel & Wamsteker (1987) and variations of the narrow Lyα and C IV were reported. The Balmer-line profiles are very broad and double peaked, and C IV and Lyα are relatively blueshifted.

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2. Data Reduction and Analysis

A total of 39 short wavelength (SWP: 1150–1980 Å) *IUE* observations have been taken between 1978 and 1992. The UV spectra were extracted from the ELBL files by a modified Gaussian extraction technique (Reichert et al. 1994) and corrected for Galactic reddening of $E(B-V) = 0.085$. To bring all spectra on to a common wavelength scale (i.e., to correct for centering errors in the *IUE* Large Aperture), the narrow C IV lines were fitted by a single Gaussian and the central wavelengths were made to coincide at 1635.9 Å.

The continuum measurements are made in two pseudo-line–free bands at 1330–1370 Å and 1775–1825 Å in the rest frame of 3C 390.3. We subdivide both C IV and Lyα into three parts: the blue side (-7000 to $-1800\,\mathrm{km\,s^{-1}}$); the red side (1800 to $7000\,\mathrm{km\,s^{-1}}$), and the core ($-1800$ to $+1800\,\mathrm{km\,s^{-1}}$). The red side was chosen in symmetry with the blue side. The emission-line flux above the continuum is integrated over the corresponding wavelength intervals. The core region in this case is of course strongly contaminated by the important contribution of the narrow line. However, the C IV red and blue side are almost free of contamination from any other lines.

From 1978 to 1993 pointed X-ray observations of 3C 390.3 have been made at 17 epochs. The 4 *ROSAT* observations taken between 1991 and 1993 are processed independently with EXSAS. In most cases, a single power-law model fits the spectrum very well.

3. Results and Implications

3.1. The Size and Kinematics of the BLR

The UV continuum light curve shows a few large events which typically last one to two years and have amplitudes of up to a factor of 5. It also suggests the presence of smaller and faster events which rise and drop in brightness by a factor of two in tens of days. The light curves of C IV and Lyα are similar to that of the continuum for the big events, except for the apparent presence of a delay in the peak brightness of some 100 days. However, the small events appear less pronounced in the emission-line light-curves.

During the *IUE* observations, the UV continuum flux varied by a factor larger than 10. The UV continuum shows the largest-amplitude variations, followed by C IV and Lyα. The core is much less variable than the blue and red side, most likely due to the contamination by the narrow line.

Cross-correlation methods have been used here to determine time lags between continuum and line light curves. The main characteristics of the cross-correlation functions (CCFs) are summarized in Table 1. It is clear that emission line and continuum variation are highly correlated, with r_{max} in the range from 0.7 to 0.9, and the variations of C IV and Lyα lag those of the continuum by about 100 days. Taking the average values for the Δt_{peak} and Δt_{cent} for both C IV and Lyα from Table 1, we find for the red part of the line $\Delta t_{red} = 65 \pm 14$ days; for the core $\Delta t_{core} = 79 \pm 11$ days, and for the blue side $\Delta t_{blue} = 124 \pm 7$ days, where the errors are the standard deviation. These errors are similar to the formal errors of the lags (Gaskell & Peterson 1987) derived from both the CCF and DCF of ± 25 days. It is thus clear that the red sides of both C IV and Lyα

respond significantly earlier to the continuum variation than the blue side. The result of directly cross-correlating the blue and red sides of the lines, suggests a time delay between the two of some 50 days, consistent with the results from the line versus continuum cross-correlation. The size of BLR in 3C 390.3 is therefore a factor of 8 less than expected by scaling the results for NGC 5548 in luminosity. The variations of the red side of the line leading those of the blue side suggests that the C IV and Lyα emitting gas is infalling towards the central object. With the large uncertainty in the time lag, it is not clear whether a rotational component is important or not.

Table 1. Main Characteristics of CCFs

First Series	Second Series	Δt_{peak} (days)	Δt_{cent}(days)[a]	r_{max}
F_λ(1800 Å)	Lyα blue	113	128	0.86
F_λ(1800 Å)	Lyα core	69	90	0.73
F_λ(1800 Å)	Lyα red	69	82	0.86
F_λ(1800 Å)	C IV blue	125	130	0.87
F_λ(1800 Å)	C IV core	69	89	0.84
F_λ(1800 Å)	C IV red	50	57	0.89
C IV red	C IV blue	45	48	0.92

[a]Centroid measured at 50% level.

3.2. Ionizing Continuum Shape

The big blue bump, often seen in the Seyfert galaxies and QSOs, is very weak or absent in 3C 390.3. The mean ratio of $F_\lambda(1350\,\text{Å})/F_\lambda(5125\,\text{Å})$ for the three nearly simultaneous (within 15 days) observations in optical and UV is 4.36, corresponding to an optical-to-UV spectral index $\alpha_{ouv} = 0.9$, where $F_\nu \propto \nu^{-\alpha_{ouv}}$.

The contamination by stellar light in the optical is small, based on the weakness of the Mg I and Fe I absorption features at 5170–5210 Å (Veilleux & Zheng 1991). The mean value of $F_\nu(1\,\text{kev})/F_\nu(1350\,\text{Å})$ for four UV and X-ray observations with separations of less than 20 days is 0.03, corresponding to a UV to X-ray spectral index $\alpha_{uvx} = 0.89$. The soft X-ray flux decreased by a factor of 2.5 between 1992 and 1993, and the soft X-ray spectral slope is consistent with a constant value $\alpha = 0.90$. The spectral indices of optical to UV, UV to X-ray, soft X-ray, and ME X-ray are all very similar for 3C 390.3, strongly suggesting that the big blue bump is very weak or absent in this object.

3.3. Variations of the Emission-Line Ratio

The C IV/Lyα line ratio is positively correlated with the continuum flux, but shows considerable scatter and is shown in Fig. 1. The correlation is better for the red side, for which the Spearmann rank correlation coefficient (r_s) is 0.67 (corresponding to the null correlation probability $P = 0.3 \times 10^{-5}$), than for the blue side ($r_s = 0.58$, $P = 10^{-4}$). To overcome the problem of time

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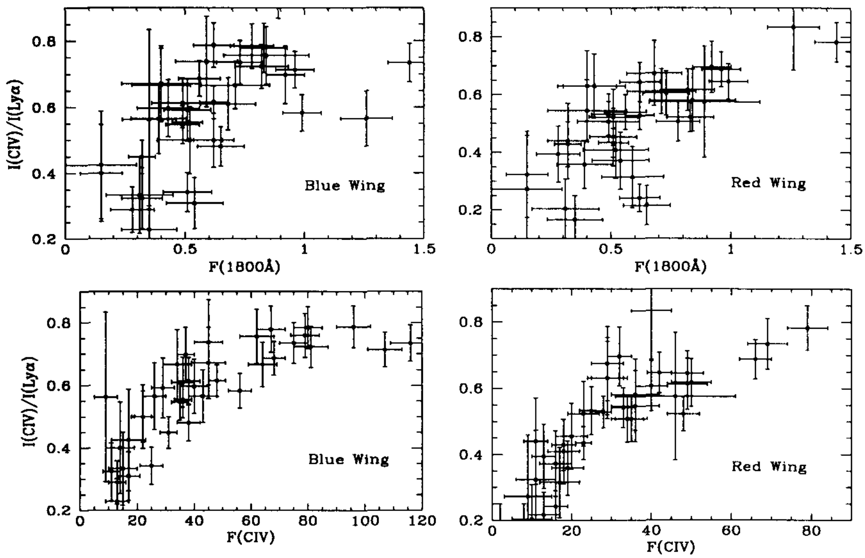

Figure 1. Plot of C IV/Lyα vs. continuum flux or corresponding C IV flux for the blue and red wing.

delays in the response of the emission lines, one could resort to correcting the correlation diagram in Fig. 1 (right) for the delay determined above, however the sampling of the light curves is not sufficient to apply such correction, as is clearly illustrated by the X-ray event in 1988. An alternative approach to correcting the relations for time-delay effects is to use the fact that the C IV line is well correlated with the continuum, and use the C IV line intensity as a measure of the continuum. Both the blue and red C IV/Lyα ratios are very well correlated with their corresponding C IV flux ($r_s = 0.815$, $P = 3 \times 10^{-9}$ and $r_s = 0.861$, $P = 10^{-11}$ for the blue and red parts, respectively). The relationship in Fig. 1 (left) is very well defined, in contrast to the C IV/Lyα relationship with the continuum, shown in Fig. 1 (right), and the C IV/Lyα ratio for the two sides of the lines merge indistinguishable into each other.

The behavior of C IV/Lyα variability might be related to the lack of a big blue bump in these objects. It is also possible that this behavior is related to the large size of the BLR, in which the ionization parameter is small and clouds have not been fully ionized.

References

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