THE ASTROPHYSICAL JOURNAL, 372:L9–L12, 1991 May 1

RAPID ULTRAVIOLET VARIABILITY IN THE BL LACERTAE OBJECT PKS 2155–304

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Received 1991 January 7; accepted 1991 February 12

ABSTRACT

This Letter reports the first clear evidence of a rapid change in the ultraviolet flux of a BL Lac object. Sophisticated analysis of 57 closely spaced *IUE* spectra yielded clear evidence of a ~12% drop in the ultraviolet flux of PKS 2155–304 over a 2 day period in 1989 October and a strong indication of a similar drop in a 5 hr period some three weeks later. These are near the fastest variations which could have been detected with these data, but they are still much slower (or weaker) variations than have been observed in the X-rays. However, they are orders of magnitude faster than Seyfert 1 ultraviolet variations. This suggests that a "standard" Seyfert 1 accretion disk may not be responsible for the ultraviolet emission from PKS 2155–304.

Subject headings: BL Lacertae objects — galaxies: individual (PKS 2155–304) — photometry — ultraviolet: spectra — X-rays: sources

1. INTRODUCTION

The "central engines" of active galactic nuclei (AGNs) are believed to be ultimately responsible for their extremely large broad-band luminosities (10^{44}–10^{47} ergs s^{-2}). Since these regions are apparently much too small ($<10^{-6}$ arcsec) to image directly, it is necessary to employ indirect methods like variability to derive structural information. BL Lac objects are the most highly variable AGNs, and observations of strong, rapid variability at radio and X-ray wavelengths have already produced good evidence for anisotropic relativistic motion and/or the presence of a supermassive black hole.

BL Lac objects are also strongly variable at ultraviolet wavelengths. The five BL Lac objects for which the *International Ultraviolet Explorer* (*IUE*) has made at least 15 repeated observations (OJ 287, Mrk 421, Mrk 501, PKS 2005–489, and PKS 2155–304) all show strong variations, generally by a factor of 2 or more, in the 13 years since *IUE* was launched (Kinney et al. 1991).

With 146 spectra in the *IUE* archives at the end of 1989, PKS 2155–304 is by far the most frequently observed BL Lac object in the ultraviolet sky. Earlier studies revealed that variations could have "doubling time scales" as short as ~10 days (Maraschi et al. 1986; Urry et al. 1988), but the light curves were grossly undersampled. This Letter focuses on the spectra obtained during a 3 week period in 1989 October. With 57 spectra obtained in three periods with total duration of about 1 week, this data set has the highest density ultraviolet sampling available to date for a BL Lac object. Thus, it offers the best chance of seeing rapid ultraviolet variations.

2. DATA

2.1. *Observations*

The *IUE* data were obtained in conjunction with simultaneous X-ray observations made with the *Ginga* satellite (Warwick et al. 1991). Observations were made with the large (10″ × 20″) aperture, and source acquisition was by blind offset from a nearby SAO star. The spectral resolution was ~7 Å. Integration times ranged from 30 to 120 minutes for the short-wavelength camera (SWP) and 10 to 60 minutes for the long-wavelength camera (LWP), with the shorter integrations occurring because of solar activity–induced high background on day 297/298.

Observing parameters, fluxes, and spectral indices for all 57 spectra are given in Table 1. The day number in the second column refers to the midpoint of the integration. The flux normalization at the reference wavelength (1600 Å for the SWP camera and 2600 Å for the LWP) and the spectral index ($S_\nu \propto \nu^\alpha$) come from power-law fits described in the next section. The last column gives the observing program code, which identifies the observers: QSLHM for observers Miller and Webb, BLLCU for Urry, and LQ029 and KQ175 for George and Warwick. Horizontal double lines indicate gaps longer than 1 day, and single lines indicate short interruptions of a few hours to a day. Of the 57 spectra, 34 were obtained during days 276–281, and 20 were obtained during days 297–299. The other three, obtained on day 284, are listed in Table 1 but omitted from the light curves because of the large temporal separation.

Optical magnitudes were obtained by Carini with the 42 inch (1.1 m) telescope at Lowell Observatory. On 1989 days

TABLE 1

A. SWP DATA

Image Number	Day Number (1989)	Integration Time (min)	F_{1600} (mJy)	α	Observing Program
37238	276.260	60	6.60 ± 0.10	−0.90 ± 0.10	QSLHM
37239	276.352	60	6.58 ± 0.10	−0.86 ± 0.09	QSLHM
37240	276.451	60	6.56 ± 0.10	−0.72 ± 0.09	QSLHM
37241	276.649	120	6.52 ± 0.09	−0.58 ± 0.08	LQ029
37242	276.688	120	6.61 ± 0.09	−0.45 ± 0.08	LQ029
37244	277.267	60	6.36 ± 0.10	−0.79 ± 0.10	QSLHM
37245	277.359	60	6.48 ± 0.10	−0.72 ± 0.10	QSLHM
37246	277.451	60	6.53 ± 0.10	−0.66 ± 0.10	QSLHM
37247	277.641	120	6.45 ± 0.09	−0.50 ± 0.09	LQ029
37248	277.779	120	6.38 ± 0.09	−0.57 ± 0.08	LQ029
37250	278.313	60	6.09 ± 0.10	−0.81 ± 0.10	QSLHM
37251	278.397	60	6.03 ± 0.11	−0.77 ± 0.11	QSLHM
37252	278.481	49	6.07 ± 0.10	−0.74 ± 0.12	QSLHM
37258	279.312	60	5.58 ± 0.10	−0.82 ± 0.10	QSLHM
37259	279.404	60	5.92 ± 0.10	−0.63 ± 0.10	QSLHM
37260	279.480	39	5.73 ± 0.11	−0.86 ± 0.12	QSLHM
37272	280.708	107	5.82 ± 0.09	−0.83 ± 0.09	KQ175
37298	284.698	120	4.29 ± 0.08	−0.71 ± 0.12	LQ029
37299	284.828	105	3.44 ± 0.07	−0.76 ± 0.13	LQ029
37451	297.920	30	7.25 ± 0.20	−0.55 ± 0.17	BLLCU
37452	297.974	30	7.43 ± 0.21	−0.31 ± 0.18	BLLCU
37453	298.019	30	6.97 ± 0.21	−0.74 ± 0.22	BLLCU
37454	298.073	30	6.43 ± 0.20	−0.70 ± 0.21	BLLCU
37455	298.119	30	6.73 ± 0.20	−0.69 ± 0.19	BLLCU
37456	298.172	30	6.59 ± 0.19	−0.76 ± 0.17	BLLCU
37460	298.912	45	7.41 ± 0.13	−0.72 ± 0.12	BLLCU
37461	298.973	60	7.24 ± 0.12	−0.53 ± 0.10	BLLCU
37462	299.042	60	7.25 ± 0.12	−0.60 ± 0.09	BLLCU
37463	299.110	60	7.27 ± 0.12	−0.78 ± 0.10	BLLCU
37464	299.179	60	7.31 ± 0.12	−0.68 ± 0.10	BLLCU

TABLE 1

B. LWP DATA

Image Number	Day Number (1989)	Integration Time (min)	F_{2600} (mJy)	α	Observing Program
16468	276.314	60	9.57 ± 0.17	−0.92 ± 0.12	QSLHM
16469	276.398	60	9.72 ± 0.17	−0.98 ± 0.13	QSLHM
16470	276.489	45	9.85 ± 0.19	−1.54 ± 0.16	QSLHM
16471	276.718	60	9.64 ± 0.17	−1.01 ± 0.13	LQ029
16472	276.848	55	9.64 ± 0.17	−0.99 ± 0.12	LQ029
16474	277.313	60	9.44 ± 0.17	−1.08 ± 0.12	QSLHM
16475	277.397	60	9.48 ± 0.17	−0.98 ± 0.13	QSLHM
16476	277.489	45	9.82 ± 0.19	−1.65 ± 0.16	QSLHM
16477	277.710	60	9.77 ± 0.17	−1.12 ± 0.12	LQ029
16478	277.847	60	9.40 ± 0.17	−1.06 ± 0.13	LQ029
16479	278.259	60	9.23 ± 0.17	−1.06 ± 0.13	QSLHM
16480	278.351	60			QSLHM
16481	278.442	55	8.91 ± 0.18	−1.16 ± 0.14	QSLHM
16487	279.259	60	8.61 ± 0.16	−1.04 ± 0.12	QSLHM
16488	279.350	60	8.59 ± 0.17	−1.21 ± 0.13	QSLHM
16489	279.442	60	8.74 ± 0.17	−0.95 ± 0.13	QSLHM
16500	280.769	46	8.60 ± 0.19	−1.01 ± 0.14	KQ175
16535	284.767	60	6.90 ± 0.16	−0.99 ± 0.15	LQ029
16640	297.951	30			BLLCU
16641	297.997	10	11.08 ± 0.51	−1.10 ± 0.38	BLLCU
16642	298.050	10	11.07 ± 0.49	−1.03 ± 0.35	BLLCU
16643	298.103	10	10.53 ± 0.46	−1.12 ± 0.36	BLLCU
16644	298.149	10	10.06 ± 0.45	−1.51 ± 0.38	BLLCU
16655	298.943	15	10.57 ± 0.28	−0.88 ± 0.20	BLLCU
16656	299.011	20	10.62 ± 0.26	−0.83 ± 0.18	BLLCU
16657	299.080	20	10.78 ± 0.25	−0.59 ± 0.17	BLLCU
16658	299.149	20	10.80 ± 0.26	−0.83 ± 0.18	BLLCU

276 and 281, $V = 13.46$ and 13.59, respectively, which is somewhat fainter than the historical average (Miller & McAlister 1983). Similarly, comparison of these *IUE* data with 8 yr of archival data (Urry et al. 1988) shows that these 57 spectra are also slightly fainter than the average ultraviolet brightness seen in 1979–1986.

2.2. *Data Reduction*

The data reduction was done at the University of Colorado *IUE* Regional Data Analysis Facility using a two-step process. First, the one-dimensional spectrum was extracted from the line-by-line file using the optimal extraction algorithm GEX (Urry & Reichert 1988), which produces considerable improvement in signal-to-noise ratio over the standard IUESIPS 9 pixel extraction by assuming a Gaussian point-spread function that changes smoothly along the dispersion direction. There was no binning in wavelength.

In the second step, a weighted power-law fit to each spectrum was used to estimate the flux and spectral slope. PKS 2155−304 has no strong ultraviolet emission or absorption features (Maraschi et al. 1986, 1988), so the uncertainty in the flux at each wavelength was taken to be the RMS variation in a 21 pixel wide moving window.

For the 29 integrations of 1 hr or more, the mean uncertainty in the flux density $\bar{\sigma} = 1.7\% \pm 0.3\%$. Examination of Table 1 and Figures 1 and 2 shows that the measured uncertainty is an accurate estimate of the repeatability of the data. Two spectra, LWP 16480 and LWP 16640, were corrupted by cosmic-ray hits and problems with the telemetry and so were excluded from further analysis.

These results are consistent with previous estimates of the repeatability seen for bright stars ($\sim$2%; see Bohlin 1990). These data were searched for possible systematic errors, but none were apparent (e.g., the flux is uncorrelated with obvious spacecraft variables such as camera temperature). Neither camera was overexposed during at least the previous 2 days. The standard corrections for the decrease in the camera sensitivities (Bohlin & Grillmair 1988) were applied.

3. RESULTS

In the first high-density sampling period, the ultraviolet flux of PKS 2155−304 underwent a clear decline of $\sim$12% (7 σ) over 2 days, seen in both cameras (Fig. 1). For these spectra, the exposures were long ($\gtrsim$1 hr), and the uncertainties in the flux are $\sim$1.5%–2%. The probability of constant flux in either camera during days 276–281 is less than 10^{-11}, according to a χ^2 test. The decline continued to day 284, with the flux dropping by $\sim$50% over 7 days.

In the high-density sampling period at the end of the monitoring (Fig. 2), the integrations were shorter, and the signal-to-noise lower (SWP integration times were 30–60 minutes, and the errors are $\sim$2%–3%), but even here large flux changes are seen within 1 day. On day 297/298, the SWP flux changed by $\sim$13% (5.5 σ) in just 5 hr. It then returned to the initial value and remained constant, on day 298/299. The χ^2 probability of constant flux at 1600 Å over this period is $\sim 10^{-7}$. The LWP integration times were even shorter (10–20 minutes), and the errors correspondingly larger ($\sim$3%–5%), so these data are too noisy to show significant variations. However, it should be

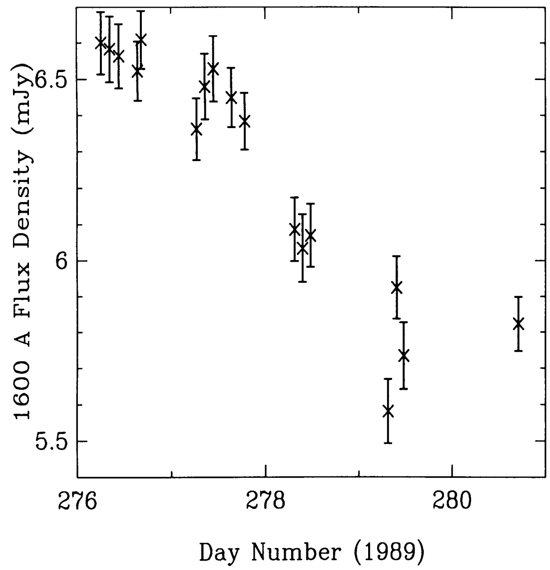

FIG. 1*a*

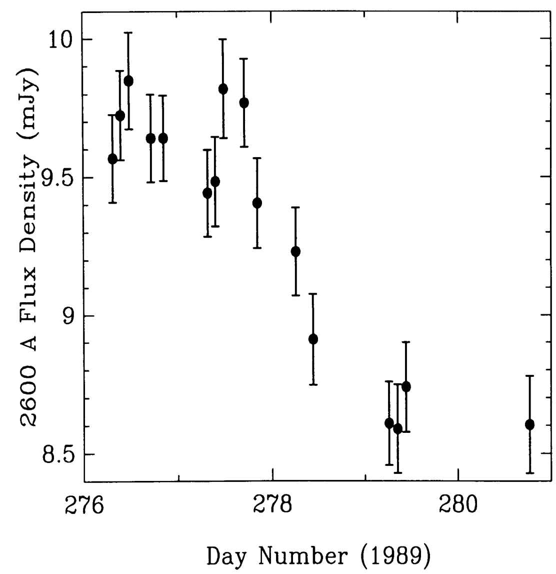

FIG. 1*b*

FIG. 1.—Ultraviolet light curve for PKS 2155−304 for days 276–280 of 1989. (*a*) SWP fluxes measured at 1600 Å; (*b*) LWP fluxes measured at 2600 Å. Note the clear simultaneous decline of ∼12% around day 278 in both cameras.

noted that the sense and magnitude of the change in LWP flux (a ∼10% drop in 4 hr in day 297/298) is the same as in the SWP data.

Table 1 reveals a systematic difference between spectral indices measured in the two cameras. The SWP spectra are flatter, with $\overline{\alpha_{\rm SWP}} - \overline{\alpha_{\rm LWP}} = 0.38$, in contrast to the general curvature of the broad-band spectrum (e.g., Treves et al. 1989). The most likely explanation is that there is a mismatch in the wavelength-dependent calibration of the SWP and LWP cameras, as has been suggested by previous studies (Urry et al. 1988; George, Warwick, & Bromage 1988), and indeed it is seen that at 2000 Å the LWP flux is ∼7% lower than the SWP flux. However this does not affect internal comparisons of flux or spectral index used in this *Letter*.

4. COMPARISON WITH PREVIOUS STUDIES

This study is the first with sufficient time resolution and signal-to-noise to resolve small outbursts in the ultraviolet flux of a BL Lac object. Although the largest previous study (Urry et al. 1988) suggested similar changes in the ultraviolet intensity of PKS 2155−304 (i.e., one case of a ∼10% change from one day to the next), it had few *IUE* spectra separated by less than 1 week and had larger quoted errors in the fluxes, making it much less sensitive to rapid variations.

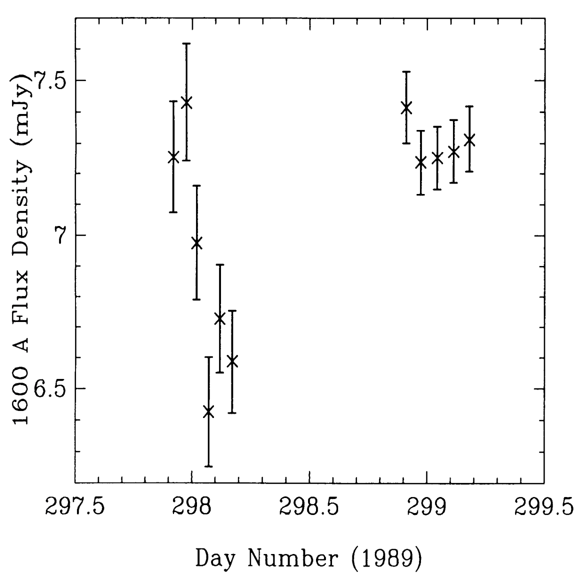

FIG. 2*a*

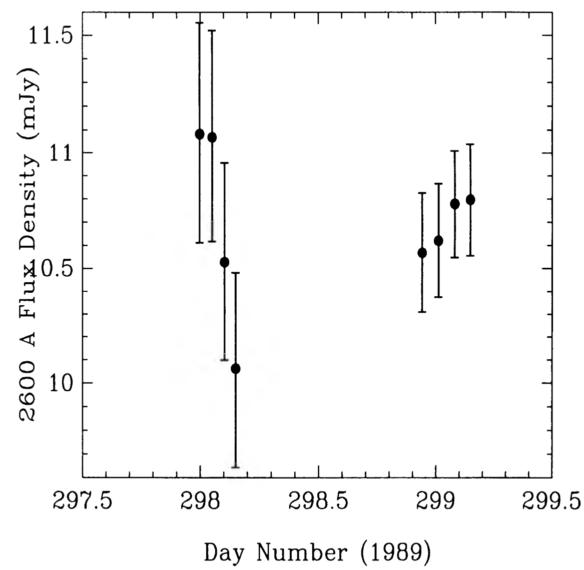

FIG. 2*b*

FIG. 2.—Ultraviolet light curve for PKS 2155−304 for days 297.5–299.5. The SWP flux declines by ∼13% in 5 hr on the first day. There is no apparent variation in the second day. In the LWP camera the errors are larger, but the sense of the variation is the same.

The decrease in optical flux is of similar amplitude and sense to that observed in the ultraviolet, suggesting that the optical and ultraviolet variations are correlated. Previous measurements have also shown that PKS 2155−304 exhibits day-to-day optical variations with an amplitude similar to that observed in the ultraviolet, and that significant optical variations can occur on times scales as short as 8 hr (Carini & Miller 1991).

Examination of the light curves suggests that the character of the ultraviolet variations can change from one day to the next. This may reflect a rather "red" fluctuation power-density spectrum (FPDS) since a "blue" FPDS (i.e., an FPDS with relatively more power on high temporal frequencies) would be more consistent from one day to the next. Tagliaferri et al. (1989) report that the X-ray FPDS (derived from a 2 day *EXOSAT* long look) showed evidence for power-law behavior with a slope of power $\propto f^{-1.5}$, which is qualitatively similar to the ultraviolet behavior.

Even for these relatively well-sampled data, it still appears that the ultraviolet variations are either slower or weaker than those seen in the X-rays. The simultaneous *Ginga* observations revealed large-amplitude X-ray variations on all time scales down to a few hours, with a factor of 5 variation over the course of the monitoring program (Warwick et al. 1991). However, PKS 2155−304 is easily detected at X-ray wavelengths in a few minutes, while the minimum usable time between *IUE* observations is $\sim$1 hr, so the ultraviolet measurements are much less sensitive to the very short time scales probed by the X-ray data. Indeed, it is clear that even the ultraviolet sampling in the present study is inadequate to properly characterize the variability. Doing so—measuring variability time scales, associated spectral changes, and FPDS—will require much longer stretches of evenly and densely sampled data.

5. DISCUSSION

The main result is that BL Lac objects can show significant ultraviolet variations over time spans as short as a few hours. These variations are poorly sampled, and the correlation with emission at other wavelengths is not well known. Nonetheless, a few general interpretive remarks are appropriate.

One model would have the ultraviolet through soft-X-ray emission produced by an accretion disk, in which case variations should occur on the dynamical time scale (Wandel & Urry 1991). However, PKS 2155−304 shows much faster ultraviolet variations than are seen in Seyfert 1 galaxies and quasars, for which the ultraviolet emission is often thought to arise from an accretion disk (e.g., Malkan, Alloin, & Shore 1989). For instance, three outbursts occurred in the recent 8 month monitoring of the highly variable Seyfert 1 NGC 5548, and little detectable difference was apparent for spectra taken less than $\sim$20 days apart (Clavel et al. 1991). This argues against the accretion disk model for PKS 2155−304, or, at the very least, indicates that an accretion disk would be very different than that thought to be seen in Seyfert 1 galaxies and quasars.

A second promising scenario is that the radio through X-ray emission of BL Lac objects is synchrotron self-Compton radiation arising within a relativistic jet. An increase in ultraviolet intensity could then be due to a sudden injection or acceleration of radiating particles, while decreases in intensity could arise as a result of the aging of the electron population. In the latter case, the ultraviolet variations will be slower than in the X-ray, as is suggested by the sparse data currently available, and should be accompanied by a spectral steepening. The correlation of ultraviolet and X-ray photons gives much stronger constraints on both these scenarios and will be discussed in detail elsewhere (Warwick et al. 1991).

The present tantalizing detection of rapid ultraviolet variability shows the importance of sampling the light curve even more densely, to determine whether the ultraviolet variations can be as fast as those seen in the X-rays. It is also important to coordinate the ultraviolet coverage with X-ray and other observations, since this provides stringent tests of models that predict how variations will propagate from one wavelength band to another. Finally, it is crucial that such sampling be regular so as to allow the application of Fourier techniques to measure the FPDS.

The authors would like to thank Tom Ayres for guidance in understanding the propagation of errors in *IUE* data, and the staff at Vilspa for help with the observations. This work was supported by the following NASA grants: NAG 5-1224 and NAG 5-1141 for Edelson, Saken, and Pike, NAG 5-1034 for Urry, and NAG 5-1141 for Miller. George acknowledges financial support from the UK SERC. The Colorado *IUE*-RDAF is supported by NASA contract NAS 5-28731.

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