MULTIWAVELENGTH MONITORING OF THE BL Lac OBJECT PKS 2155-304.

I. IUE Observations

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ABSTRACT

Daily monitoring of PKS 2155-304 with the IUE satellite throughout November 1991 has revealed dramatic, large-amplitude, rapid variations in the ultraviolet flux of this BL Lac object. Many smaller, rapid flares are superimposed on a general doubling of the intensity in 30 days. During the four-day period when sampling was roughly continuous, the rapid flaring has a quasi-periodic nature, with peaks repeating every $\sim$ 0.7 days. Short- and long-wavelength ultraviolet light curves are well correlated with each other, and with the optical light curve deduced from the Fine Error Sensor (FES) on IUE.

1. INTRODUCTION

The most puzzling aspect of AGN has always been their high power output coupled with the small emission region inferred from rapid variability. By definition blazars (the collective name for BL Lac objects and Optically Violently Variable quasars) are the most rapidly variable AGN. Blazars are radio-loud and have a smooth continuum (especially compared to Seyfert galaxies and radio-quiet quasars) spanning the wavelength range from the radio through the soft X-ray.

In the last decade, considerable progress has been made interpreting the fast variability and the broad-band spectra of blazars as emission from relativistic jets (Blandford & Rees 1978; Königl 1981; Urry & Mushotzky 1982; Ghisellini, Maraschi & Treves 1985; Worrall *et al.* 1986; Hutter & Mufson 1986; George, Warwick & Bromage 1988). These models have been very successful, in the sense that they usually fit the continuum spectrum over nearly 10 decades in wavelength. Unfortunately, the parameters of the model are rarely well-determined because acceptable fits can be produced with a number of assumptions which are to some extent arbitrary.

The missing ingredient is variability. The degeneracy of multiple model solutions vanishes or is greatly reduced when variability information is added because the derived size limits represent strong constraints for the models. Although some studies have recognized this (George *et al.* 1988, Mufson *et al.* 1990, Treves *et al.* 1989), the available sampling to date — only a few spectra, spaced far apart in time – has been sparse, uneven, and inadequate.

For this reason, we designed a monitoring program that would produce high-quality light curves in several bands, including ultraviolet, optical, and X-ray. The object selected for our study, PKS 2155-304, is one of the brightest extragalactic objects in the ultraviolet and X-ray sky. It was discovered with the HEAO1 X-ray satellite (Schwartz *et al.* 1979) and identified as a BL Lac object because of its radio emission and polarized optical continuum (Griffiths *et al.* 1979). The redshift is not well established but is probably close to $z = 0.1$ (Bowyer *et al.* 1979; Falomo *et al.* 1991). PKS 2155-304 has previously been observed to be highly variable at both ultraviolet (Maraschi, Tanzi, & Treves 1986; Urry *et al.* 1988; Edelson *et al.* 1991) and X-ray (Snyder *et al.* 1980, Morini *et al.* 1986, Treves *et al.* 1989, Sembay *et al.* 1992) wavelengths.

The campaign was carried out in 1991 November. Unprecedented spectral coverage in the ultraviolet, extreme ultraviolet, and soft-X-ray was provided by the combination of IUE, the Rosat Wide Field Camera (WFC), and the Rosat Position Sensitive Proportional Counter. Ground-based observations covered optical to radio frequencies. The IUE data set itself is of exceptional quality, with about 100 spectra in each of the two IUE cameras and daily sampling for a month plus 4 days of quasi-continuous observations. Here we present some preliminary results of the ultraviolet part of the monitoring campaign. A more complete description can be found in Urry *et al.* (1992). The observations and data analysis are described in § 2, and the results in § 3. The results are discussed briefly in § 4.

2. OBSERVATIONS AND DATA ANALYSIS

2.1 Observing Strategy

The variability time scales of BL Lac objects in general, and even this best-studied object PKS 2155-304 in particular, were not well measured, so the observing plan bracketed a range of time scales. In order to measure moderate time scale variations (days to a week) we scheduled at least one half IUE shift daily from 1 November to 29 November (except on November 8, due to a scheduling conflict). In order to study short-term variability, four and a half days in the middle of the campaign (10.7 - 15.3 November) were devoted to nearly continuous coverage using ~3 full shifts per day.

The short-wavelength (SWP) and long-wavelength (LWP) IUE cameras were exposed alternately, with typical integration times of 55 and 25 minutes, respectively. This allowed us to get two pairs of spectra during each half IUE shift, absent any operational problems.

Just before each SWP or LWP exposure, counts from the Fine Error Sensor (FES), the optical monitor on IUE, were measured on target and on background.

2.2 Spectral Extraction

Spectra were extracted from each of the 202 IUE images using the Slit-Weighted Extraction Technique (SWET) of Kinney, Bohlin & Neill (1991). which is publicly available through the IUE Regional Data Analysis Facility. Details of the SWET procedure can be found in Kinney *et al.* (1991).

There is another well-known slit-weighted technique, the Gaussian extraction or GEX method (Urry & Reichert 1988), which assumes the cross-dispersion profile is a Gaussian. We have also extracted all the spectra using GEX, and compared this to the SWET results. Differences found using the two extraction methods do not affect the results significantly.

The FES counts were converted to optical magnitudes using the recently developed algorithm of Perez and Loomis (1991), which takes into account the background due to scattered light. PKS 2155-304 was assumed to have color B–V=0.26 throughout the month, which is the mean value measured contemporaneously with ground-based optical telescopes, and did not change much during the monitoring period (Smith *et al.* 1992).

2.3 Spectral Corrections

The extracted net fluxes were converted to absolute flux using the recent IUE calibration of Bohlin *et al.* (1990). A correction was made for degradation in the SWP sensitivity (Bohlin & Grillmair 1988, as updated through 1990 by Bohlin, private communication); the extrapolation beyond 1990 is somewhat uncertain (but not by more than 1%). No sensitivity correction was made to the LWP net flux.

There is no evidence for internal reddening in PKS 2155-304; in particular, the soft X-ray spectrum (e.g., Canizares and Kruper 1984, Madejski 1985) indicates the column density of absorbing cool gas along the line of sight is commensurate with the interstellar medium in our Galaxy in that direction. Using an IUE-based conversion (Shull & Van Steenberg 1985), this column density of $N_H = 1.78 \times 10^{20}$ atoms cm^{-2} (Stark *et al.* 1992) corresponds to $E(B-V) \sim 0.034$. Therefore spectra were dereddened using $E(B-V) = 0.034$ and the standard curve from Seaton (1979). The dereddened flux is 30% greater at 1400 Å and 20% greater at 2800 Å than the observed flux, and the fitted energy spectral index is typically 0.06 flatter in the SWP and 0.28 flatter in the LWP. Further discussion focuses on the dereddened spectra.

2.4 Spectral Fitting

Using an iterative, chi-squared minimization fitting routine, the dereddened IUE spectra were fitted to a simple power–law model of the form:

$$f_\lambda = b_1 \left(\frac{\lambda}{\lambda_0}\right)^{b_2} \tag{1}$$

The fit parameters are the normalization, b_1, at fiducial wavelength λ_0, and slope b_2. We will however give the more commonly used energy index, α, where $F_\nu \propto \nu^{-\alpha}$, which is related to b_2 via $\alpha = 2 + b_2$. The wavelength ranges over which the data were fitted were 1230–1950 Å for the SWP camera (which excludes the geo-coronal Lyman-α region) and 2100–3100 for the LWP camera. Wavelength regions affected by SWP camera artifacts (Crenshaw, Bruegman & Norman 1990), at 1277–1281 Å, 1286–1290 Å, and 1660–1666 Å, were excluded, as was the region 1470–1540 Å, in which unusual features were apparent in many of the spectra. The power–law fit is generally good for all the spectra. The normalization is at 1400 Å for SWP spectra and 2800 Å for LWP spectra. These wavelengths are close to the flux-weighted means of each band ($\sim$ 1560 Å and $\sim$ 2568 Å, respectively, for $\alpha = 1$), so that the uncertainty on the derived flux is small.

2.5 Error Analysis

The detection and evaluation of variability requires an accurate treatment of errors. A continuum estimate from direct measurement would have a relatively large error bar (the variance in some interval around that wavelength), including both local statistical noise and fixed-pattern noise. Like most BL Lac objects, however, PKS 2155-304 has a smooth and approximately featureless spectrum which is well fitted by a simple power–law model. The flux calculated from a fitted power law gives a much smaller error bar than direct measurement because information from the full band is used.

The estimation of errors in the flux and spectral index involved several steps: First, the SWET error vector was propagated through the fitting procedure to get initial uncertainties for the parameters of the power-law fit, b_1 and b_2. Next, both Δb_1 and Δb_2 were increased by a factor equal to the mean of the reduced chi-squared distribution, $\sqrt{\langle\chi^2_\nu\rangle}$, (where $\langle\chi^2_\nu\rangle = 3.76$ for the SWP and $\langle\chi^2_\nu\rangle = 2.42$ for the LWP). This is equivalent to scaling up the SWET error vector so that $\langle\chi^2_\nu\rangle = 1$ in both cases. The final error estimate on the flux at λ_0 is equal to the quadrature sum of the scaled error on b_1 and 1.25% of b_1. The final error estimate on the spectral index was derived by increasing the scaled error on b_2 by 1.95 for the SWP, 2.46 for the LWP, and 2.48 for the combined SWP-LWP fits, so that it represents the 1 σ error for the observed differences between adjacent measurements of α. Since this assumes no intrinsic variation between adjacent measurements, it is if anything an overestimate of the error on the spectral index.

A procedure similar to that used for determining $\Delta\alpha$ was used to estimate the global mean uncertainty in the FES-derived magnitude. The normalized error distribution for $\Delta V = 0.08$ mag had variance equal to one and was consistent with a Gaussian distribution centered on zero. This is therefore a good estimate of the mean uncertainty in the FES magnitudes; it does not take into account relative errors among FES measurements or any systematic offset from other optical measurements (e.g., Smith *et al.* 1992, Courvoisier *et al.* 1992), such as might be due to incorrect color corrections.

3. RESULTS

3.1 Ultraviolet Light Curves

The light curves for the full month and for the central period are shown in Figure 1. During the intensive monitoring, the ultraviolet flux varied by ~30% in several distinct flares that are well-sampled apart from a possible dip during the 7-hour gap on 11 November. The width of these rapid flares is roughly half a day; if we define a doubling time scale as $\tau_D = \Delta t(\overline{F}/\Delta F)$, then values for these flares are typically less than 5 days. There are no obvious differences between the time scales for flaring or decaying intensity. These are comparable to, but much better sampled than, the fastest ultraviolet variations seen previously in this or any other object (e.g., Edelson 1992).

The fractional variability is comparable for the two bands: both light curves show a doubling of flux, and in both bands the variance is about 15% of the mean flux. The optical light curve shows exactly the same trends as the ultraviolet light curves, on both long and short time scales, albeit with larger error bars.

The SWP, LWP, and FES light curves are all highly correlated, with no discernable lag (the upper limit is $\lesssim 0.1$ days). The discrete cross-correlation functions (Edelson & Krolik 1988) for SWP versus LWP and SWP versus FES are shown in Figure 2. Both cross-correlation functions are asymmetric, in the sense of higher correlation at positive lags, which correspond to the longer wavelength emission following the short-wavelength emission.

The autocorrelation functions of the SWP, LWP and FES fluxes were also computed. The SWP and LWP give similar results, while the FES amplitude is generally smaller, probably because the relative errors are larger. (For the SWP and LWP, the behavior of the autocorrelation functions suggests the estimates of flux errors were about right.) On long time scales, the autocorrelation functions suggest smooth "red" power spectra, with relatively more power on longer time scales. However, on shorter time scales (using the data from the well-sampled, five-day intensive monitoring) they are modulated strongly with a period of $\sim$0.7 days. The SWP and LWP autocorrelations for this case are shown in Figure 3. This quasi-periodic behavior can be seen going through a full five cycles directly in the light curves (Fig. 1b), despite the uncertainty introduced by the gap at 11.5 November. Further runs of intensive monitoring are needed to verify whether this is a repeatable, possibly periodic or quasi-periodic phenomenon.

3.3 Spectral Shape

Taking the reddening into account, the spectrum in the SWP and LWP ranges is well described by a single power law, i.e., there is no spectral "curvature" in the ultraviolet band. The flatness of the UV spectral index means that the peak of the luminosity emitted from this BL Lac object is in the far-ultraviolet, as noted by previous authors. PKS 2155-304 is one of the few extragalactic objects detected in the Rosat WFC survey (Pounds 1991); thus, using the simultaneous data from IUE and Rosat we will be able to actually measure the total luminosity and spectral shape from 10^{15} to 5×10^{17} Hz.

The spectral index of the SWP did change significantly during the monitoring campaign. A non-parametric Spearman Rank-Order Correlation test shows a likely correlation between F_{1400} and α_{SWP} ($P = 1.7 \times 10^{-3}$). The correlation improves when one looks at change in spectral index versus change in flux; $\Delta\alpha$ and ΔF are correlated with probability 6.6×10^{-7}. The sense of the correlation is that the spectrum hardens as it brightens, as found previously (Maraschi *et al.* 1986, Urry *et al.* 1988, Edelson 1992). The improvement of the correlation when one looks at *changes* in F and α indicates there is little long-term memory of spectral shape. Further analysis of the spectral behavior is in progress.

4. CONCLUSION

The campaign has up to now demonstrated at least the need of frequent sampling for these rapidly variable extragalactic objects. For the first time, after more than a decade of observations of this object, a particular timescale ($\sim$0.7 days) has become apparent. Its significance should be confirmed by further observations. It is tempting to believe that it may be associated with some physical time scale, perhaps to a periodic or quasi-periodic phenomenon. The associated $\frac{\Delta L}{\Delta t} \simeq 3 \times 10^{40} erg/sec^2$ is not extreme but may become so when the bolometric correction determined from the simultaneous Rosat data (Brinkmann *et al.* 1992) is taken into account.

In BL Lac objects the UV emission is supposed to be nonthermal, due to synchrotron emission from relativistic electrons. The radiative loss times of such particles are estimated to be much shorter than the observed timescale so the latter should be associated with some nonstationary macroscopic process of acceleration and/or confinement of the relativistic particles. These mechanisms must be closely related to the "central engine" possibly through a magnetohydrodynamic wind driven by a spinning black hole. Similar timescales are observed in the X-ray emission of Seyfert galaxies, which is also thought to originate close to the central engine. We expect that the combined information from the multiwavelength campaign will allow further progress in the understanding of BL Lac objects (Edelson *et al.* 1992).

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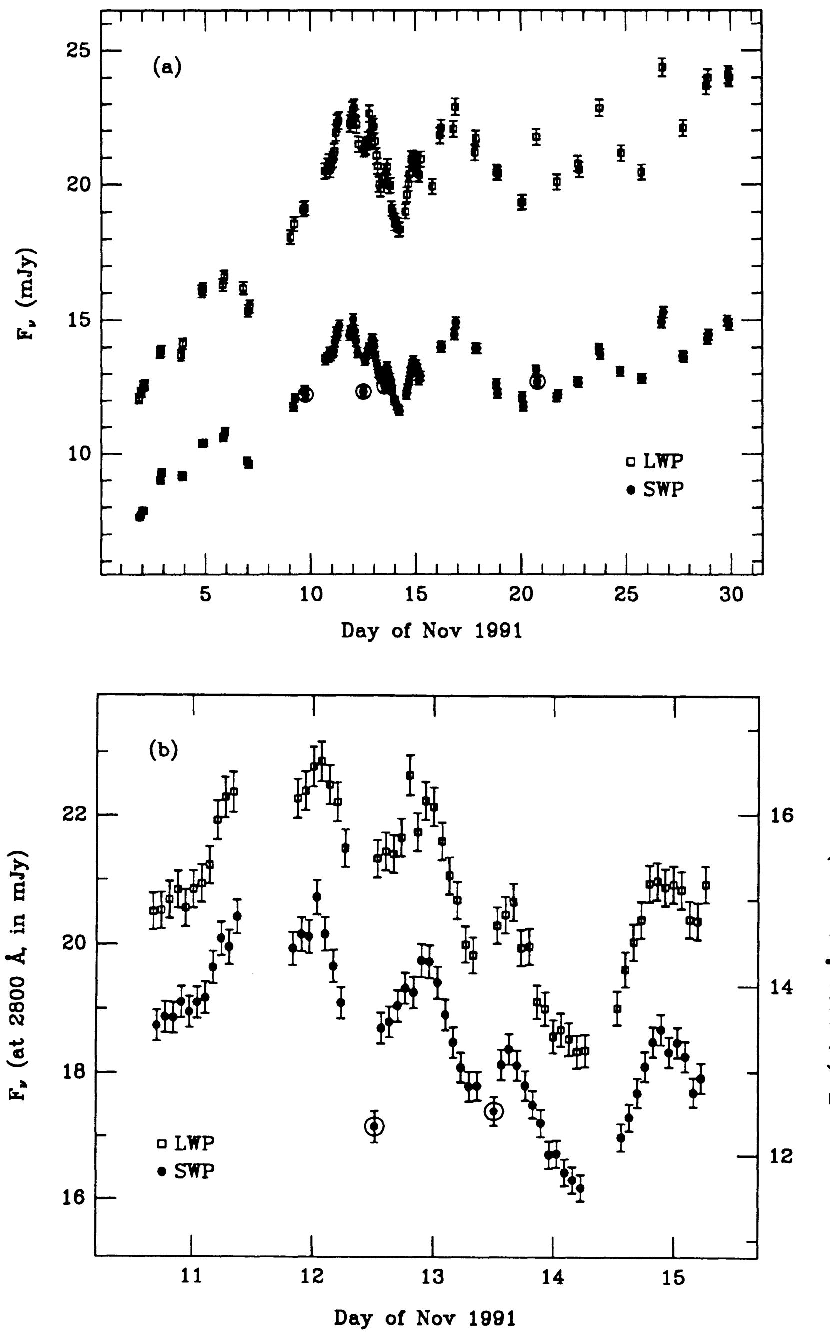

Fig. 1. — Ultraviolet light curves of PKS 2155-304. *(a)* The full light curve, with fitted fluxes at 2800 Å (*open squares*) and 1400 Å (*filled circles*) on the same scale. Both long- and short-wavelength fluxes doubled during the month, with no apparent lag. *(b)* Expanded view of the intensive monitoring period, during which IUE observations were nearly continuous. The LWP scale is at left, the SWP scale at right. Many rapid flares, with duration of about half a day, have clearly been well-sampled. Five cycles of a quasi-periodic nature can be seen, but true periodicity cannot be established without a longer data train.

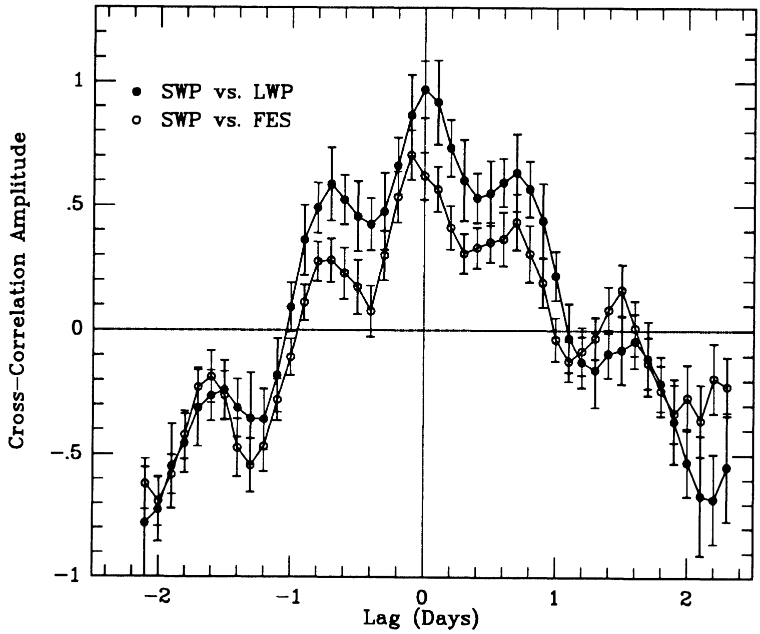

Fig. 2. — Cross-correlations of SWP (1400 Å) flux versus LWP (2800 Å) flux and SWP versus FES flux. The light curves are highly correlated, with zero lag (with an upper limit of less than a few hours), and the curves are asymmetric in the sense of the short-wavelength emission leading the longer wavelength emission.

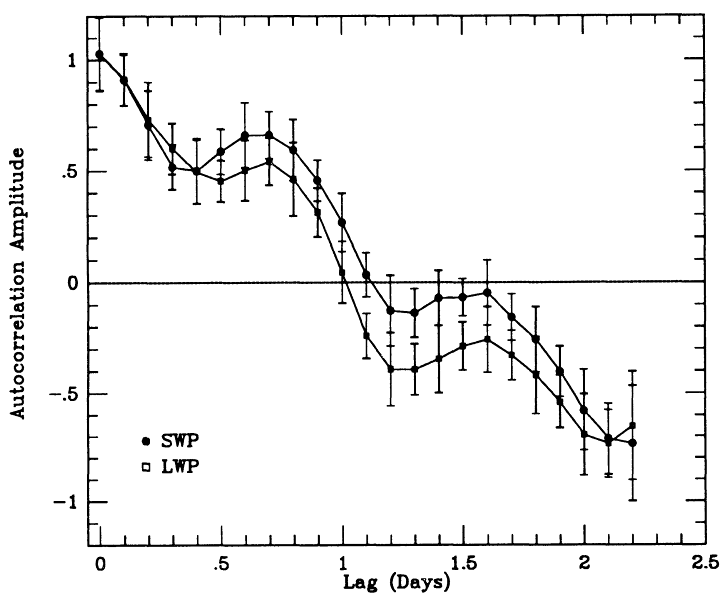

Fig. 3. — Auto-correlation functions for SWP (1400 Å) and LWP (2800 Å) light curves calculated for the 5-day intensive monitoring period only. The SWP and LWP autocorrelation functions are very similar, and both show a peak at a lag of about 0.7 days.