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X-RAY VARIABILITY OF THE BL LACERTAE OBJECT PKS 2155 – 304 IN THE 0.1–6 keV RANGE

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ABSTRACT

PKS 2155 – 304 was observed with *EXOSAT* at five different epochs in 1983–1984 for a total of 30 hr. A variation of a factor 10 in the 1–6 keV range was found. On one occasion the intensity of the source increased by a factor 4 in 4 hr, with evidence of spectral hardening. The associated luminosity variation was $dL/dt \approx 10^{42}$ ergs s^{-2} ($H = 100$ km s^{-1} Mpc^{-1}). The results yield constraints on the emission models of the source.
Subject headings: BL Lacertae objects — galaxies: individual — X-rays: sources

I. INTRODUCTION

PKS 2155 – 304 is a bright BL Lac object ($m_v \approx 12$–14), discovered through its X-ray emission (Agrawal and Riegler 1979; Schwartz *et al.* 1979). A redshift $z = 0.117$ has been determined from the spectrum of a faint surrounding nebulosity (Bowyer *et al.* 1984). The source has been extensively observed in optical, UV, and X-rays (e.g., Snyder *et al.* 1979; Urry and Mushotzky 1982; Miller and McAlister 1983; Maraschi *et al.* 1983, Canizares and Kruper 1984).

A series of observations of PKS 2155 – 304 was carried out with *EXOSAT* (see Taylor *et al.* 1981 for a description of the instrumentation) in 1983 October and November and in 1984 November as part of an ongoing multifrequency study of the source. The source was observed at five different epochs for a total of 30 hr of exposure time. Preliminary results for the 1983 observations were given in Morini *et al.* (1985). In this *Letter* we present and discuss results about the time variability observed with the Medium Energy (ME) argon counters in the energy range 1–6 keV and with the Low Energy (LE) telescope.

II. OBSERVATIONS

The data we discuss in this *Letter* were obtained with the ME argon counters (the energy range 1–6 keV is here chosen because of the highest signal-to-noise ratio) and with the Channel Multiplier Array (CMA) at the focus of the LE telescope in conjunction with the 3000 Å Lexan filter (bandpass from 0.05 to 2 keV). Special care has been taken in the ME background subtraction: all the observations were performed with half of the ME experiment offset to monitor the background, swapping the ME arrays during the observations, except in the case of 1983 November 29 when the source was observed with the same ME half-experiment during all the observation time. The ME background was subtracted: (1) using the simultaneous background in the off-source half experiment, corrected by the extrapolated difference between the two ME arrays as we derived from slew data from the same observation; and (2) with the "array swap" technique, i.e., adding the two spectra obtained for each half-experiment after subtraction of the corresponding off-source background. The two techniques differ in the sense that the former removes the instantaneous background although yielding larger statistical uncertainties, while the latter corrects for a mean background averaged over the whole observation time. The first one was used for all the light curves, and for the 1983 November 29 spectrum, the second one for all the other spectra.

Table 1 gives the starting times and durations of the LE and ME observations and the corresponding average count rates. The LE and ME light curves for the five observations, binned over 400 seconds, are shown in Figure 1 (*upper and*

TABLE 1

LOG OF THE X-RAY OBSERVATIONS OF PKS 2155−304

UT Time	Filter	LE Count Rate (counts s^{-1})	UT Time	ME 1–6 keV Count Rate (counts s^{-1})	ME Hardness Ratio (3–6 keV/1–2 keV)
		1983 Oct 31			
00:54–01:44.......	Lexan	0.775 ± 0.018	00:25–14:56	1.78 ± 0.02	1.45 ± 0.04
01:47–02:51.......	Al-Pa	0.227 ± 0.009	...	...	...
02:54–04:47.......	Boron	0.038 ± 0.004	...	...	...
04:50–05:40.......	Lexan	0.743 ± 0.017	...	...	...
05:44–07:01.......	Al-Pa	0.227 ± 0.010	...	...	...
10:20–12:24.......	Boron	0.034 ± 0.004	...	...	...
12:37–13:38	Lexan	0.627 ± 0.014	...	...	...
14:08–16:02.......	Al-Pa	0.188 ± 0.006	...	...	...
		1983 Nov 29			
18:47–19:03.......	Lexan	1.271 ± 0.083	17:33–22:06	3.69 ± 0.07	1.67 ± 0.05
19:06–19:42.......	Al-Pa	0.422 ± 0.034	...	...	...
20:10–21:34.......	Boron	0.077 ± 0.006	...	...	...
21:45–22:05.......	Lexan	1.189 ± 0.048	...	...	...
		1984 Nov 6			
13:52–14:25.......	Lexan	1.843 ± 0.035	13:24–13:57	4.85 ± 0.11	1.60 ± 0.11
14:29–15:12.......	Al-Pa	0.644 ± 0.017	15:11–16:04	7.12 ± 0.09	1.71 ± 0.07
15:16–17:28.......	Boron	0.141 ± 0.005	17:42–18:15	10.15 ± 0.12	1.74 ± 0.06
17:32–18:08.......	Lexan	2.087 ± 0.050	...	...	...
		1984 Nov 7			
09:58–10:30.......	Lexan	1.946 ± 0.041	09:35–10:18	4.47 ± 0.11	1.32 ± 0.09
10:33–11:18.......	Al-Pa	0.712 ± 0.022	11:26–12:10	9.86 ± 0.10	1.46 ± 0.04
11:22–13:35.......	Boron	0.180 ± 0.006	13:37–14:10	17.59 ± 0.14	1.62 ± 0.04
13:39–14:11	Lexan	2.990 ± 0.048	...	...	...
		1984 Nov 11			
11:43–12:04.......	Lexan	2.205 ± 0.096	11:01–15:01	6.92 ± 0.05	1.51 ± 0.03
12:08–12:40.......	Al-Pa	0.784 ± 0.058	...	...	...
12:44–14:22.......	Boron	0.136 ± 0.006	...	...	...
14:26–15:03.......	Lexan	2.088 ± 0.041	...	...	...

central panels). Short term (hours) and long term (months) variability is apparent. The dynamic range of the 1–6 keV intensity is more than one order of magnitude, the highest recorded with a single instrument, but similar to the historical variability record of the source (Urry, Mushotzky, and Holt 1986). During the short exposures (about 5 hr) of 1984 November 6 and 7, the ME rates increased by a factor 2 and 4, respectively. A linear fit of the ME light curve between 13:39 UT and 13:49 UT of November 7 yields $dF/dt = 7.9$ $(\pm 0.6) \times 10^{-3}$ counts s^{-2}, corresponding to a variation time scale $\tau = F(dF/dt)^{-1} \approx 2200$ s. The overall LE light curve mimics the ME one, but with a smaller dynamic range. It is noticeable that comparing the observations of 1983 October 31, 1983 November 29, and 1984 November 11, when the source was steady within each observation, there is a linear relation between the LE and ME count rates, while during the rapid brightenings of 1984 November 6 and 7 the LE count rate increase was much smaller than the ME one. This points to a spectral hardening during flares.

Within the ME range the spectral variability can be directly explored through the hardness ratio. In Figure 1 (*lower panels*) the ratio of counts between 3–6 keV and 1–2 keV is shown binned either over 800 or 1,600 s, depending on the intensity of the source. The only evidence for spectral variability is found on 1984 November 7, when the intensity variation was largest. Within this observation the hardness ratio indicates a hardening of the spectrum with time (and therefore with increasing intensity): a χ^2 test against constancy of the ratio yields a chance probability of less than 2×10^{-3}. A softening during the 1984 November 11 observation is suggested by Figure 1, but the significance is only 4×10^{-2}.

The energy spectrum has been studied by fitting to the ME data a power law with a low-energy cutoff due to photoelectric absorption. For the 1984 November 6 and 7 epochs, power laws have been fitted to the start and end portions of 2,000 s, and to the central portion of 3,000 s of data. In each case the 90% confidence contours in the N_H-α plane were

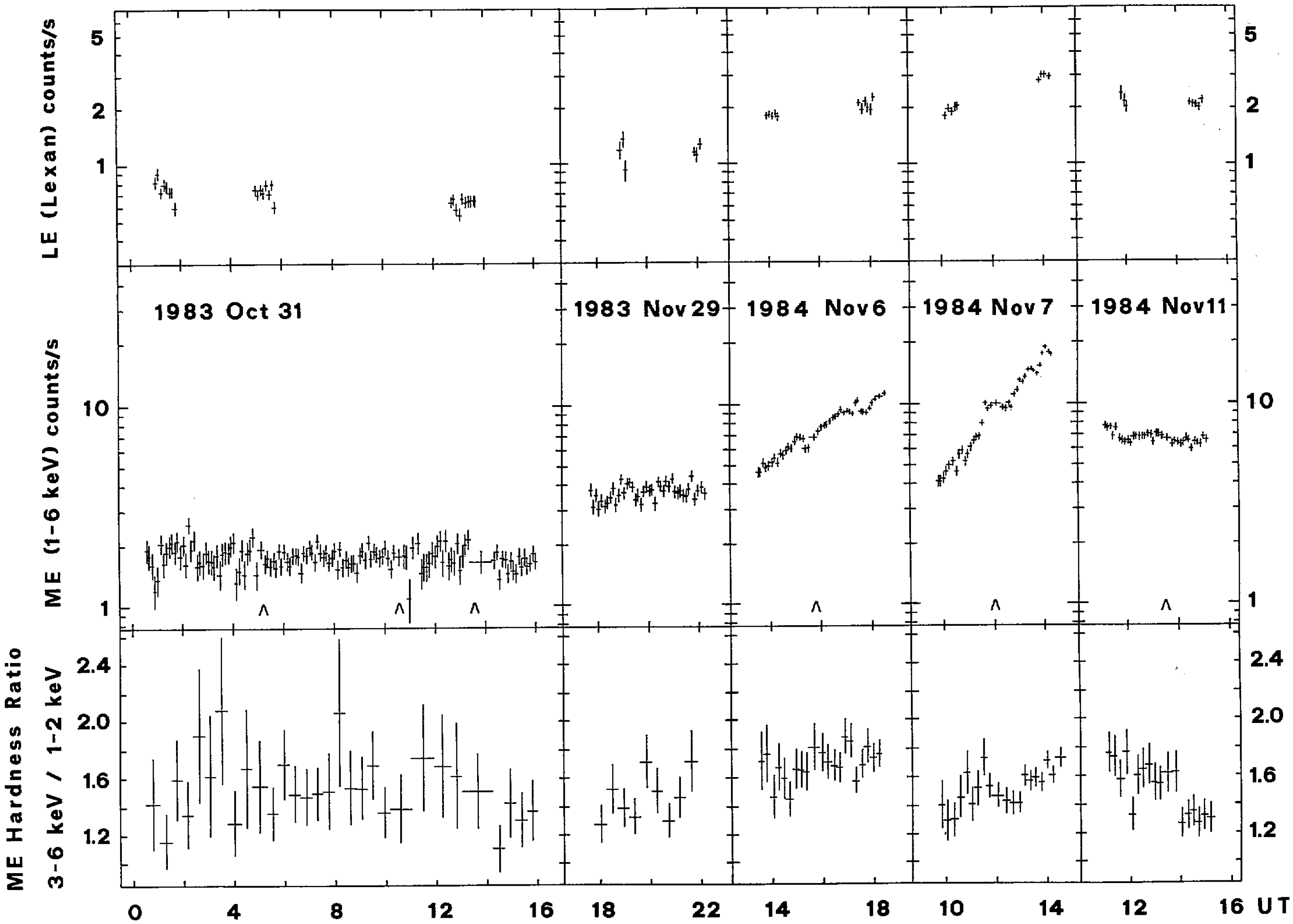

FIG. 1.—X-ray light curves of PKS 2155−304 on 1983 October 31, November 29 and 1984 November 6, 7, and 11. *Upper panels*: LE + 3000 Å Lexan filter (bandpass from 0.05 to 2 keV) count rates; *central panels*: ME argon counters (1–6 keV) count rates; *lower panels*: ME hardness ratio (3–6 keV/1–2 keV). Arrows indicate the ME array swaps.

TABLE 2

SPECTRAL PARAMETERS OF PKS 2155−304

	ME (1–6 keV)			ME (1–6 keV) + LE 1 (3000 Å Lexan filter)		
DATE (1)	Spectral Index[a] (2)	N_H (10^{20} cm^{-2}) (3)	1–6 keV Flux (ergs cm^{-2} s^{-1}) (4)	Spectral Index[a] (5)	N_H (10^{20} cm^{-2}) (6)	0.1–6 keV Flux (ergs cm^{-2} s^{-1}) (7)
1983 Oct 31	2.60 (2.52–2.76)	0 (< 34)	0.28×10^{-10}	2.60 (2.52–2.68)	1.07 (0.75–1.48)	0.97×10^{-10}
1983 Nov 29	2.81 (2.52–3.12)	55 (< 130)	0.69×10^{-10}	2.58 (2.47–2.70)	1.37 (0.93–2.02)	1.84×10^{-10}
1984 Nov 6 start.......	2.89 (2.40–3.58)	94 (< 260)	1.03×10^{-10}	2.50 (2.30–2.73)	0.94 (0.47–1.81)	2.40×10^{-10}
1984 Nov 6 mid	2.71 (2.50–2.92)	67 (20–120)	...	...	...	...
1984 Nov 6 end	2.51 (2.27–2.81)	33 (< 106)	1.57×10^{-10}	2.38 (2.26–2.50)	1.23 (0.80–1.81)	3.70×10^{-10}
1984 Nov 7 start.......	2.82 (2.59–3.39)	0 (< 118)	0.73×10^{-10}	2.83 (2.58–3.06)	1.78 (0.95–2.95)	2.83×10^{-10}
1984 Nov 7 mid	2.81 (2.65–2.99)	76 (38–117)	...	...	...	...
1984 Nov 7 end	2.54 (2.34–2.74)	46 (< 94)	3.06×10^{-10}	2.37 (2.29–2.44)	1.64 (1.25–2.26)	6.46×10^{-10}
1984 Nov 11	2.92 (2.80–3.03)	52 (26–76)	1.35×10^{-10}	2.70 (2.66–2.75)	1.95 (1.71–2.57)	3.71×10^{-10}

[a] Photon spectral index α, $dN/dE = k\ E^{-\alpha}$.

examined. In Table 2, columns (2)–(4), we report the best-fit values and the extremes of a box encompassing the contours. On three occasions the derived column densities are larger than the upper limit to the galactic column density ($N_H < 4 \times 10^{20}\,\mathrm{cm}^{-2}$; Maraschi *et al.* 1981) at more than 90% level.

In the hypothesis of a single power-law spectrum in the whole energy range, the combination of the ME and LE data provides a constraint on the absorbing column densities. The LE data are treated as a single channel with a 10% error added to the statistical one in order to take into account the uncertainties in the calibration of the CMA detector. The results are reported in Table 2, columns (5)–(7). All the values for the absorbing column densities derived from the combined ME+LE fits are of the order of $10^{20}\,\mathrm{cm}^{-2}$. They are smaller than the limit on the galactic absorption, even when the ME data gives a significantly larger value of N_H. This implies either that the absorption present above 1 keV does not affect lower energies (e.g., absorption by ionized material), or a softer spectral component must be included in the spectrum at low energies, or both. The result agrees with the findings of Urry, Mushotzky, and Holt (1986) based on the comparison of the Solid State Spectrometer and the Image Proportional Counter of the *Einstein Observatory*. A soft excess below 0.6 keV was in fact observed together with an unusual absorption feature by the *Einstein* Objective Grating Spectrometer (Canizares and Kruper 1984). Our observations suggest that the soft component has a distinct temporal behavior during the episodes of rapid variability.

III. DISCUSSION

Assuming isotropic emission the total 0.1–6 keV luminosity ranges between 1.5×10^{45} and 10^{46} ergs s^{-1} ($H = 100$ km s^{-1} Mpc^{-1}). This is comparable with the UV (1200–3000 Å) luminosity, $L_{UV} = 3 \times 10^{45}$ ergs s^{-1} (see Maraschi *et al.* 1983), and greatly exceeds the luminosity in other bands. The maximum derivative of the luminosity, which corresponds to the maximum derivative of the ME 1–6 keV light curve, is given by

$$(dL/dt)_{\max} = C(dF/dt)_{\max} = 2.0 \times 10^{42}\ \mathrm{ergs\ s^{-2}}, \quad (1)$$

where the count rate-to-luminosity conversion factor C is obtained from the spectral fit of the last part of the 1984 November 7 observation as reported in Table 2. The observed values of L and dL/dt imply severe constraints on the source structure. Suppose that the luminosity does not exceed the Eddington limit, this fixes a lower value of the mass

$$M > 10^8\ M_\odot, \quad (2)$$

which corresponds to a gravitational radius $R_g = 2GM/c^2 = 3 \times 10^{13}$ cm. The associated light crossing time is $t_g = 1{,}000$ s. The observed minimum time scale (less than 3,000 s) implies therefore an emission region at most $3R_g$ in size, which is per se rather restrictive.

A more stringent limit on the admissible variability time scale is derived taking into account the presence of matter and the diffusion of photons within the emission region (Cavallo and Rees 1978; Fabian 1979). This yields

$$dL/dt < 2 \times 10^{41}\ (k/0.1)\ \mathrm{ergs\ s^{-2}}, \quad (3)$$

where k is the efficiency of mass to energy conversion in the emission region.

If the mechanism generating the X-ray power is accretion onto a compact object, k is expected to be of the order of 0.1 for spherical or disk accretion onto a Schwarzschild black hole. The observed luminosity variation therefore violates the theoretical upper limit for this class of models by a factor of 10. Within accretion models this violation could be alleviated allowing super-Eddington luminosities and anisotropic radiation as may be associated with a supercritical disk. The observed X-ray spectrum however is significantly steeper than expected in models considering either Comptonization or bremsstrahlung as basic emission processes (see, e.g., Mészáros 1983; Maraschi, Roasio, and Treves 1982). The above considerations refer to the case where the observed variability is not amplified by relativistic beaming. If such effect were present the intrinsic luminosity variation could be smaller than the apparent one by a factor δ^5, where δ is the usual Doppler factor. In this case accretion models remain viable for the energy source, but the observed radiation should be associated with a relativistic jet, while the emission connected directly to accretion would be much weaker than the observed one.

Alternatively one may interpret the observed variation as implying values of k larger than 1. This implies that the emitting particles are repeatedly accelerated by processes not involving rest mass transport. A similar inference had been drawn previously from the synchrotron interpretation of the ultraviolet spectrum (e.g., Begelman, Blandford, and Rees 1984). The ultimate energy source would then be outside the emission region and one may argue that it can be the rotational energy of a black hole which powers the jet. In this scenario the bulk motion of the jet does not need to be highly relativistic in order to explain the data presented here.

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