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X-RAY AND OPTICAL OBSERVATIONS OF X-RAY–SELECTED BL LACERATAE OBJECTS

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ABSTRACT

Results from several X-ray and optical observations of five X-ray–selected BL Lacertae objects are reported. X-ray light curves covering periods of up to 6 yr reveal that the X-ray flux from these objects does not show large amplitude trends over this time scale. Variations of up to 2 mag have been observed in the optical. The soft X-ray spectra of three objects have been measured with the *EXOSAT* Medium Energy detectors. Energy spectral indices range between 1 and 2. In one case (1E 1415.6+2557) evidence for photoelectric absorption in excess of that due to the local interstellar medium has been found. A new optical flare from 1E 1402.3+0416, with rise and decay time of order of a few weeks, has been detected. For the case of 1E 1207.9+3945, which was observed 18 times in the X-rays and did not show evidence for luminosity variability, comparison between Monte Carlo simulated and observed counts shows that the data set is still consistent with a constant flux having superposed flares similar to that detected in 1E 1402.3+0416, occurring every few days or weeks depending on rise and decay time. The implications of the observed steep spectra for the emission processes in these BL Lac objects are discussed.

Subject headings: BL Lacertae objects — radiation mechanisms — X-rays: sources — X-rays: spectra

I. INTRODUCTION

Among the 112 X-ray sources of the *Einstein* Medium Sensitivity Survey (MSS: Maccacaro *et al.* 1982; Stocke *et al.* 1983; Gioia *et al.* 1984), four were identified with BL Lacertae objects. These four objects, together with four other BL Lac objects discovered in the all-sky survey of Piccinotti *et al.* (1982), constitute the only complete (flux-limited) sample of BL Lac objects presently available. Stocke *et al.* (1985) have investigated the radio and optical properties of the four MSS BL Lac objects and concluded that, mainly because of their low radio luminosity and lower ratio between the active nucleus and the host galaxy brightness, they generally differ from the classical radio-selected BL Lac objects and are very similar to well-known objects like Mrk 501 and Mrk 421 when seen at greater distances (see Stocke *et al.* 1985 for details). The X-ray properties of the four MSS BL Lac objects are poorly known, being limited to the discovery observations as serendipitous sources. We have therefore observed them with the *EXOSAT Observatory* in an attempt to study their X-ray time variability and to estimate their spectral shapes. At the same time we have carried out optical monitoring of these objects, to investigate any correlation between variability in the two wavebands and to study the short-term optical behavior. The analysis of two *EXOSAT* observations of one object (1E 1402.3+0416) has already been reported by Giommi *et al.* (1986). In this paper we present the results of the X-ray and optical observations of all four MSS BL Lac objects. We also include the results from an *EXOSAT* observation of a fifth serendipitous *Einstein* X-ray source (1E 1415.6+2557) identified with a BL Lac object by Halpern *et al.* (1986), but which was not included in the MSS because of its proximity to the edge of the Imaging Proportional Counter (IPC) field of view.

In § II we describe the analysis of the observations; in § III we present the X-ray and optical light curves of the four MSS BL Lac objects. Whenever the X-ray sources were detected with sufficient statistics in the Medium Energy experiment (ME), we give the results of the spectral fits (assuming a power law) between 2 and 6 keV. Finally a discussion of the results is given in § IV.

II. OBSERVATIONS AND DATA ANALYSIS

The *EXOSAT Observatory* is described by Taylor *et al.* (1981). The payload includes an imaging telescope in front of the Channel Multiplier Array (CMA), sensitive in the 0.05–2.0 keV range (the Low Energy experiment—LE), and a large area proportional counter array (the Medium Energy experiment—ME). The CMA (de Korte *et al.* 1981) has no intrinsic energy resolution, but multicolor photometry may be performed using different filters.

During the observations presented here, the 3000 Å Lexan filter, which provides maximum photon throughput for most spectral shapes, and the Al/Par filter were used. Source count rates have been estimated in square boxes of size such as to maximize the signal-to-noise ratio. The background intensity was obtained from source-free regions of the CMA images in the vicinity of the sources. After the background subtraction, the source counts were corrected for the appropriate Point Spread Function and for the vignetting effect. Effective exposure times were calculated taking into account the telemetry and the instrumental dead times.

The ME experiment (Turner, Smith, and Zimmermann 1981) consists of an array of passively collimated proportional counters sensitive to X-rays with energy between 1 and ~20 keV and provides moderate spectral resolution (FWHM ~1 keV at 7 keV). The ME experiment is generally operated with half of the area pointed at the target, and with the other half pointed at a nearby source-free region, to monitor possible background variations. In order to optimize the subtraction of

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the instrumental background, the two halves are swapped at roughly midobservation. With this procedure, the sensitivity for detection of weak sources is limited by systematic uncertainties in the background subtraction process to about 2×10^{-12} ergs cm^{-2} s^{-1} in the 1–6 keV band.

Data from the *EXOSAT* archive have been reanalyzed and combined with our own observations to maximize the number of data points in the light curve of 1E 1207.9+3945. The *Einstein Observatory* data have also been reanalyzed in order to take into account the results of our ME spectral analysis. The MSS BL Lac objects have been optically monitored on time scales of months and days, often simultaneously or quasi-simultaneously with the X-ray observations. The RCA CCD camera attached to the 61 cm telescope of the Whipple Observatory with a broad-band red-sensitive filter, approximating the Johnson (1966) *R* band, was used. For each field a group of surrounding stars was used as a brightness standard and the normal CCD reduction procedure was followed (see Stocke *et al.* 1985 for details). In Table 1 we present the 1985–1986 photometric data for the four MSS BL Lac objects. From repeated observations, it is found that the measurement errors are 0.02 mag and the zero point of the magnitude scale, as obtained from the field standards, is uncertain by 0.03 mag. The *R* band is centered around 4.3×10^{14} Hz and $R = 17$ mag corresponds to a flux density of 0.45 mJy.

III. RESULTS

Table 2 summarizes the X-ray observations of the five BL Lac objects. In order to allow a direct comparison between *Einstein* and *EXOSAT* data, fluxes are calculated in the energy range 0.3–3.5 keV and are corrected for absorption in our Galaxy. Column (1) gives the observation date. Column (2) gives the flux intensity as measured by the *Einstein* IPC derived using the spectral parameters listed in Table 3; the associated errors were calculated adding the statistical errors to the extreme values allowed by the uncertainties in the spectral parameters. Columns (3) and (4) give the *EXOSAT* count rates both in the thin Lexan and Al/Par filters, while columns (5) and (6) give the corresponding X-ray fluxes obtained with the same procedure used for the case of the IPC fluxes.

The results of the spectral analysis are summarized in Table 3 where column (1) gives the source name; column (2), the energy index in the band 0.05–6 keV derived fitting the ME and LE data under the assumption of a power-law spectral shape; column (3) gives the equivalent hydrogen column density (N_H) required by the X-ray data; column (4), the amount of N_H in our Galaxy in the direction of the source from Stark *et al.* 1987; column (5) gives the source flux in the 2–6 keV band.

TABLE 1

1985–1986 PHOTOMETRY

Date (1986)	*R* Magnitude
1E 0317.0+1835	
Nov 3[a]	17.37
Jan 11	17.44
Jan 17	17.40
Jan 29	17.46
Feb 19	17.50
Feb 20	17.40
Feb 22	17.50
Feb 23	17.35
Feb 24	17.46
Feb 25	17.39
Feb 25	17.35
Feb 27	17.39
Feb 28	17.39
Mar 5	17.30
Mar 7	17.36
Mar 8	17.35
Mar 14	17.34
1E 1235.4+6315	
Jan 11	17.77
Jan 13	17.83
Jan 19	17.81
Jan 21	17.70
Jan 22	17.71
Feb 22	17.69
Mar 7	17.76
Mar 8	17.64
Mar 16	17.70
1E 1402.3+0416	
Dec 4[a]	16.65
Jan 19	16.63
Jan 21	16.55
Jan 30	16.42
Feb 20	16.18
Feb 21	16.21
Feb 22	16.19
Mar 3	16.28
Mar 5	16.32
Mar 6	16.40
Mar 7	16.38
Mar 8	16.33
Mar 10	16.39
Mar 15	16.37
1E 1207.9+3945	
Jan 11	19.11
Jan 13	18.95
Jan 17	18.90
Jan 21	18.91
Mar 8	18.87

[a] 1985.

a) *1E 0317.0+1835*

Two *EXOSAT* observations of this object were performed on 1985 January 14 and February 9. During the first observation, which lasted about 4700 s, only the thin Lexan filter was used, while both the Lexan and Al/Par filters were used during the second, longer, 16,100 s exposure.

The X-ray energy spectrum was obtained by fitting ME and LE data collected during the second observation. For a power-law model (Fig. 1), the fit yields a χ^2 of 2.7 for 7 d.o.f., an energy index of 1.0(−0.4, +0.5, 90% confidence) and an equivalent hydrogen column density of $1.15(-0.8, +1.5) \times 10^{21}$ atoms cm^{-2} (90% confidence), consistent with the amount measured in our Galaxy in the direction of the source (9.6×10^{20} atoms cm^{-2}; Stark *et al.* 1987). The two Lexan count rates do not show any flux variation in the source. Assuming the spectral slope to be within the 90% confidence range of the *EXOSAT* measurement and N_H equal to the galactic value, we report in Table 2 the flux values obtained during the *Einstein* and *EXOSAT* observations. Comparison between these measurements indicates that the 1985 flux agrees, within the errors, with the flux measured in 1980 at the time of the original IPC discovery observation (Fig. 2*a*). The optical monitoring covers a period from 1982 to 1986 (Fig. 2*b*). During the period covered by the *EXOSAT* observations, no variation has been detected

TABLE 2

HISTORY OF SOFT X-RAY FLUX

OBSERVATION DATE (1)	*Einstein* FLUX (0.3–3.5 keV) (1×10^{-12} ergs cm^{-2} s^{-1}) (2)	*EXOSAT* COUNT RATE (1×10^{-3} counts s^{-1})		*EXOSAT* FLUX (0.3–3.5 keV) (1×10^{-12} ergs cm^{-2} s^{-1})	
		Thin Lexan (3)	Al/Par (4)	Thin Lexan (5)	Al/Par (6)
1E 0317.0+1835					
1980 Feb 10	$14.8^{+1.7}_{-2.5}$	...	...	...	...
1985 Jan 14	...	8.9 ± 1.8	...	$10.3^{+4.7}_{-3.1}$	...
1985 Feb 9	...	7.9 ± 1.3	7.6 ± 1.4	$9.2^{+3.7}_{-2.5}$	$11.8^{+4.9}_{-3.2}$
1E 1207.9+3945					
1979 May 18–20	$1.3^{0.2}_{-0.3}$	...	...	...	...
1979 Dec 12–13	$1.0^{+0.2}_{-0.2}$	...	...	...	...
1983 Jul 11	...	8.5 ± 1.7	...	$1.8^{+1.6}_{-0.9}$	...
1983 Jul 12	...	7.2 ± 0.7	...	$1.6^{+1.1}_{-0.7}$	...
1983 Nov 7	...	5.5 ± 1.7	3.2 ± 0.9	$1.2^{+1.2}_{-0.7}$	$1.5^{+1.2}_{-0.7}$
1983 Nov 11	...	7.1 ± 2.2	5.7 ± 1.7	$1.5^{+1.7}_{-0.8}$	$2.7^{+2.2}_{-1.4}$
1983 Nov 15	...	6.0 ± 1.8	3.6 ± 0.8	$1.3^{+1.4}_{-0.7}$	$1.7^{+1.2}_{-0.8}$
1983 Nov 18	...	<8.2	...	...	...
1983 Dec 17	...	6.3 ± 0.7	...	$1.4^{+1.0}_{-0.7}$	...
1984 Apr 7	...	8.4 ± 1.7	4.9 ± 1.1	$1.8^{+1.6}_{-0.9}$	$2.3^{+1.7}_{-1.0}$
1984 Apr 18	...	9.4 ± 1.8	3.4 ± 1.1	$2.0^{+1.8}_{-1.0}$	$1.6^{+1.4}_{-0.8}$
1984 Jun 2	...	<14	<5.8	...	...
1984 Dec 16	...	7.4 ± 2.4	3.3 ± 1.2	$1.6^{+1.7}_{-0.9}$	$1.6^{+1.4}_{-0.9}$
1984 Dec 19	...	6.3 ± 1.7	3.9 ± 1.3	$1.4^{+1.3}_{-0.8}$	$1.8^{+1.6}_{-0.9}$
1984 Dec 22	...	...	4.5 ± 1.4	...	$2.1^{+1.8}_{-1.1}$
1985 Jan 2	...	5.9 ± 1.8	2.5 ± 0.9	$1.3^{+1.3}_{-0.8}$	$1.2^{+1.0}_{-0.7}$
1985 Jan 27	...	6.4 ± 0.9	4.0 ± 0.7	$1.4^{+1.1}_{-0.7}$	$1.9^{+1.2}_{-0.8}$
1986 Mar 3	...	8.9 ± 1.9	...	$1.9^{+1.8}_{-1.0}$	...
1E 1235.4+6315					
1980 Apr 20	$1.5^{+0.4}_{-0.3}$	...	...	...	...
1985 Mar 20	...	2.8 ± 0.6	...	$0.5^{+0.5}_{-0.2}$	...
	...	2.7 ± 0.3[a]	...	$0.5^{+0.5}_{-0.2}$	...
1E 1402.3+0416					
1979 Jul 23	$0.9^{+0.1}_{-0.1}$	...	...	...	...
1980 Jul 10[b]	$3.7^{+1.3}_{-1.6}$	...	...	...	...
1985 Jan 31–Feb 1	...	27.8 ± 2.1	...	$5.3^{+0.9}_{-1.7}$	...
1985 Jan 31–Feb 2	...	14.0 ± 2.5	...	$2.6^{+0.9}_{-1.0}$	...
1985 Feb 6	...	12.0 ± 2.5	...	$2.3^{+0.7}_{-1.0}$	...
1985 Jul 6	...	13.4 ± 1.4	6.4 ± 1.5	$2.5^{+0.6}_{-0.8}$	$2.8^{+0.8}_{-1.0}$
1E 1415.6 + 2557					
1979 Jun 29	$19.9^{+0.7}_{-1.1}$[c]	...	...	...	...
1986 Mar 4–5	...	60.3 ± 1.7	...	$42.5^{+3.4}_{-3.2}$	...

[a] Observation performed with 4000 Å (thick) Lexan filter.

[b] Observation performed with HRI.

[c] This flux is probably underestimated due to IPC rib obscuration; see text for details.

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TABLE 3

RESULTS OF SPECTRAL ANALYSIS

Source Name (1)	Spectral Slope Energy Index (2)	N_H (atoms cm^{-2}) (3)	Galactic N_H (atoms cm^{-2}) (4)	Flux (2–6 keV) (ergs cm^{-2} s^{-1}) (5)
1E 0317.0+1835	$1.0^{+0.5}_{-0.4}$	$1.2^{+1.5}_{-0.8} \times 10^{21}$	9.6×10^{20}	$(9.4 \pm 0.6) \times 10^{-12}$
1E 1207.9+3945[a]	...	...	2.1×10^{20}	...
1E 1235.4+6315[b]	...	...	1.7×10^{20}	$<3.8 \times 10^{-12}$
1E 1402.3+0416[c,d]	$1.6^{+0.3}_{-0.1}$	$2.0^{+10.}_{-2.0} \times 10^{20}$	2.0×10^{20}	$(3.9 \pm 0.8) \times 10^{-12}$
1E 1415.6+2557	$2.0^{+0.2}_{-0.2}$	$8.0^{+2.5}_{-2.5} \times 10^{20}$	1.6×10^{20}	$(4.6 \pm 0.3) \times 10^{-12}$

[a] Confused with NGC 4151.

[b] 3 σ upper limit.

[c] During bright state.

[d] From Giommi *et al.* 1986.

in the optical range. In the 1985–1986 observing period the source showed almost no systematic change in luminosity (see Table 1). Its brightness can be described as steady at the 10% level, but with apparently random 10% fluctuations from night to night.

b) *1E 1207.9+3945*

This object is located only ~5′ from the nearby and well-studied Seyfert galaxy NGC 4151. The *EXOSAT* archive is thus rich with CMA fields containing 1E 1207.9+3945.

Because of the proximity to NGC 4151, the ME detector, with a field of view of 45′ FWHM, cannot be used to study the X-ray spectrum of 1E 1207.9+3945. The lack of determination of the spectral index increases the uncertainty in the comparison of the *Einstein* and *EXOSAT* data. The *Einstein* data have been reanalyzed assuming an energy spectral slope of 1.5 ± 0.5 (similar to that measured for other X-ray–selected BL Lac objects and an equivalent hydrogen column density of 2.1×10^{20} atoms cm^{-2}, equal to the amount found in the Galaxy in the direction of 1E 1207.9+3945 (Stark *et al.* 1987). In Table 2 we report the *Einstein* and *EXOSAT* fluxes derived using spectral energy indices $\alpha = 1.0$ and $\alpha = 2.0$. The computed fluxes are fully compatible with a constant value of 1.4×10^{-12} ergs cm^{-2} s^{-1} (0.3–3.5 keV). The *EXOSAT* X-ray light curve of 1E 1207.9+3945 covering an interval of more than 3 yr is shown in Figure 3*a*, together with the results of the

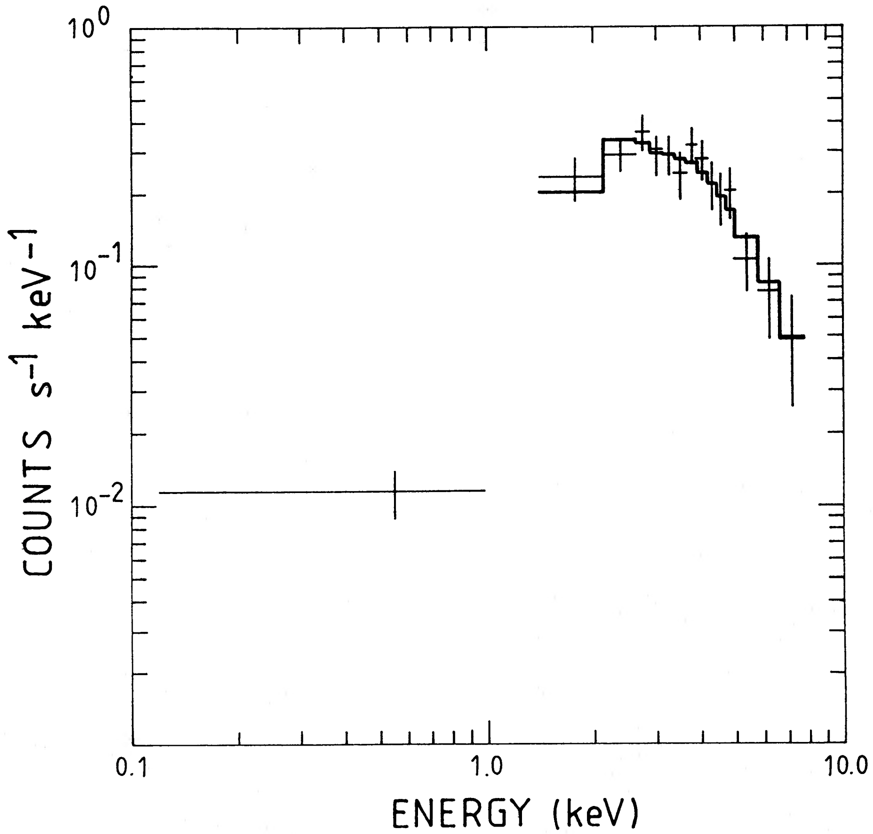

FIG. 1.—Combined ME and LE spectrum of 1E 0317.0+1835. The first data point corresponds to the thin lexan measurement. The best-fit power law model is shown as a histogram superposed on the data.

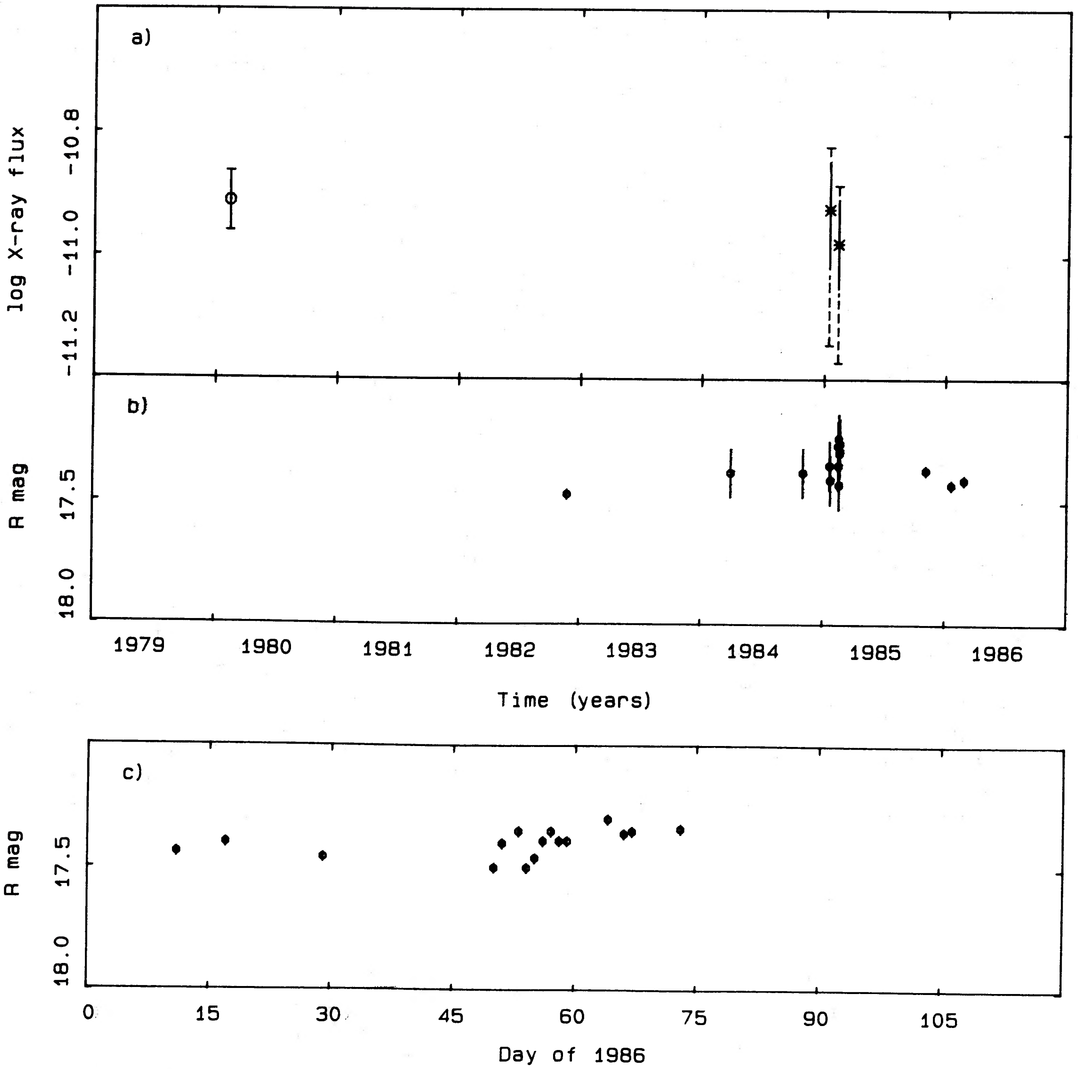

FIG. 2.—X-ray and optical light curves of 1E 0317.0+1835. In this figure and in Figs. 3, 4, and 5 frame (*a*) shows the estimated range of the X-ray flux in the 0.3–3.5 keV band. Solid error bars reflect statistical errors only; dashed lines give the total error interval including uncertainties due to the poor knowledge of the spectral parameters. Open circles correspond to *Einstein* IPC measures; open triangles, to *Einstein* HRI; and asterisks, to *EXOSAT* CMA measurements. Frame (*b*) shows the results of the optical monitoring, and frame (*c*) shows the details of the 1986 optical monitoring while only two average points are plotted in frame (*b*). Scales of *R* mag and X-ray flux axes have been chosen so that equal separations between two points correspond to equal flux ratios in the two bands.

optical monitoring in the period 1982–1986 (Fig. 3*b*). The optical magnitude undergoes significant changes between 1982 and 1984, with a half-magnitude dimming in 1983. At the beginning of 1986 there is an indication of a slight brightening on a time scale of 2 days, followed by the usual flickering behavior (see Fig. 3*c* and Table 1).

c) *1E 1235.4+6315*

This source shows an optical light curve somewhat similar to that of 1E 1402.3+0416 with 0.3–0.5 mag oscillations between 1982 and 1984 (see Table 3 in Stocke *et al.* 1985) and a burst of approximately 1 mag at the beginning of 1985 (Fig. 4*b*). At the beginning of 1986 the source was almost as bright as a year before and did not show any variability during the 2 months' monitoring, apart from a significant flickering at the 10% level (Fig. 4*c*), which seems to be a common behavior for these objects. 1E 1235.4+6315 was observed only once with *EXOSAT* in 1985 March and was detected as a weak source in the CMA. No detection was achieved in the ME. In order to compare the flux measured by the *EXOSAT* and *Einstein* satellites, we assume a power-law spectrum with energy index of 1.5 ± 0.5 and no intrinsic absorption (i.e., $N_{\rm H} = 1.7 \times 10^{20}$ atoms cm^{-2}; Stark *et al.* 1987). Under these assumptions, the *Einstein* flux (in the 0.3–3.5 keV band) ranges between 1.2×10^{-12} and 1.9×10^{-12} ergs cm^{-2} s^{-1}. The flux measured during the *EXOSAT* observation is lower (see Fig. 3*a* and Table 2), but for a spectral slope of 1 or flatter, consistency with a constant flux can be obtained.

d) *1E 1402.3+0416*

This object underwent a large X-ray and optical burst in 1985 January. The results of the observations relevant to this event have been reported elsewhere (Giommi *et al.* 1986). We recall that 1E 1402.3+0416 exhibited, at least during its high state, a power-law spectrum with an energy index of 1.6 (+0.3, −0.1). A follow-up *EXOSAT* observation was performed on 1985 July 6 using the thin Lexan and Al/Par filters. The count rates are reported in Table 2, and, within the statistical errors,

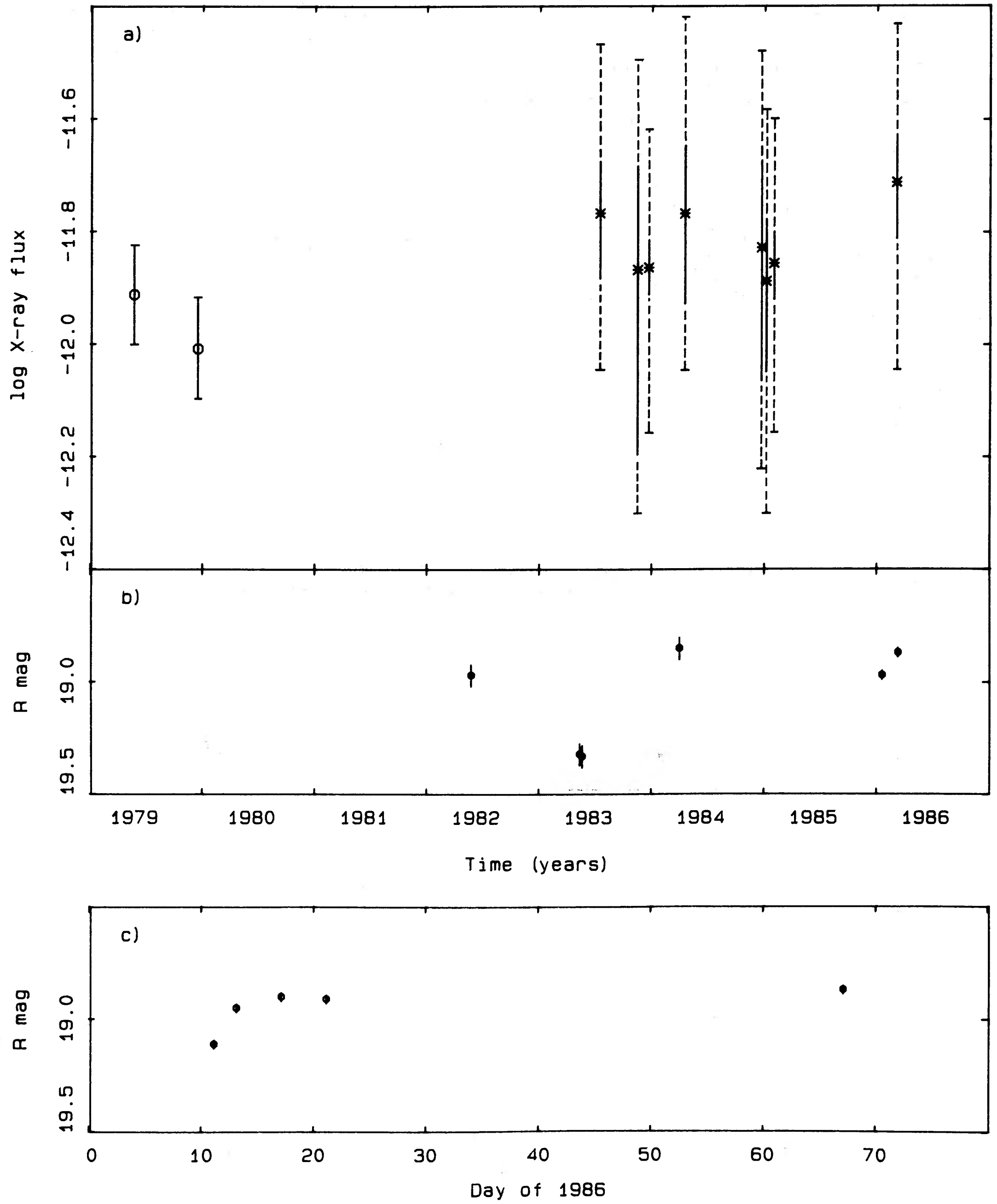

FIG. 3.—X-ray and optical light curves of 1E 1207.9+3945. In order to avoid a too crowded graph, points from observations performed within a few days of each other have been combined and only the resulting average count rates have been plotted.

they are the same as those measured at the end of the X-ray flare (see also Fig. 5*a*).

New optical photometric measurements were obtained on 14 nights between 1985 December 4 and 1986 March 15 (Table 1 and Fig. 4*c*). The object flared by at least 0.5 mag between 1986 January 19 and February 20. The data suggest a rise time similar to the decay time, this being comparable to the one observed during the 1985 February burst.

e) *1E 1415.6+2557*

This BL Lac object was observed by *EXOSAT* on 1986 March 4 for 31,630 s. Since 1E 1415.6+2557 is located only ~35′ from the relatively bright X-ray source NGC 5548, the pointing of the instrument was offset to avoid confusion in the ME detectors. In order to monitor possible rapid luminosity changes in the soft X-ray energy band, only the thin Lexan filter was used in conjunction with the CMA. No short term variability was detected during the observing period, and the resulting average count rate was $(6.03 \pm 0.17) \times 10^{-2}$ counts s^{-1}. A power-law energy spectrum was fitted to the ME plus the LE data yielding a χ^2 of 4.5 for 7 d.o.f. with an energy index of 2.0 ± 0.2 and a hydrogen column density of $(8.0 \pm 2.5)^{20}$ atoms cm^{-2} (Fig. 6). This absorption is significantly higher than that due to interstellar matter (1.6×10^{20} atoms cm^{-20};

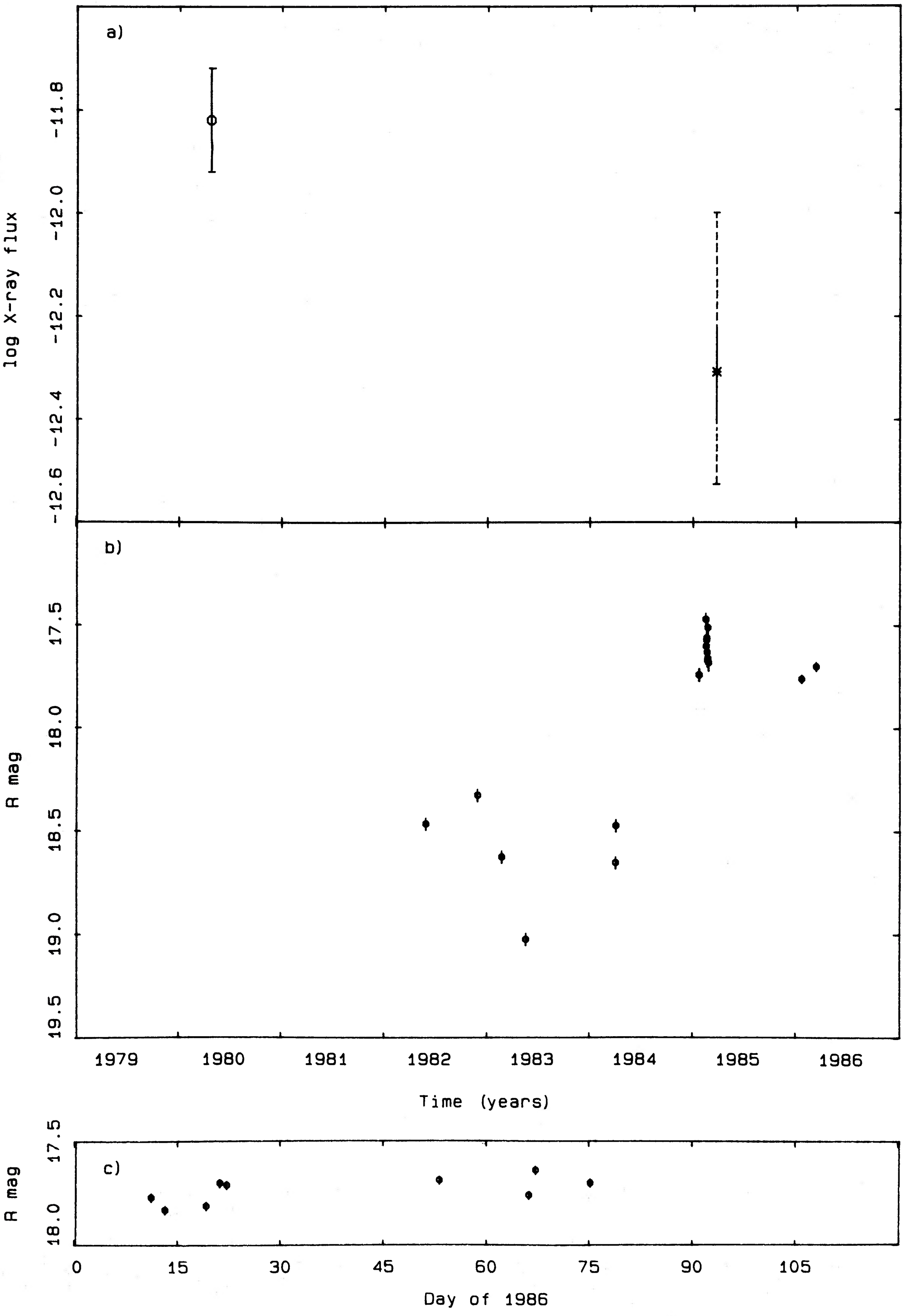

FIG. 4.—X-ray and optical light curves of 1E 1235.4+6315

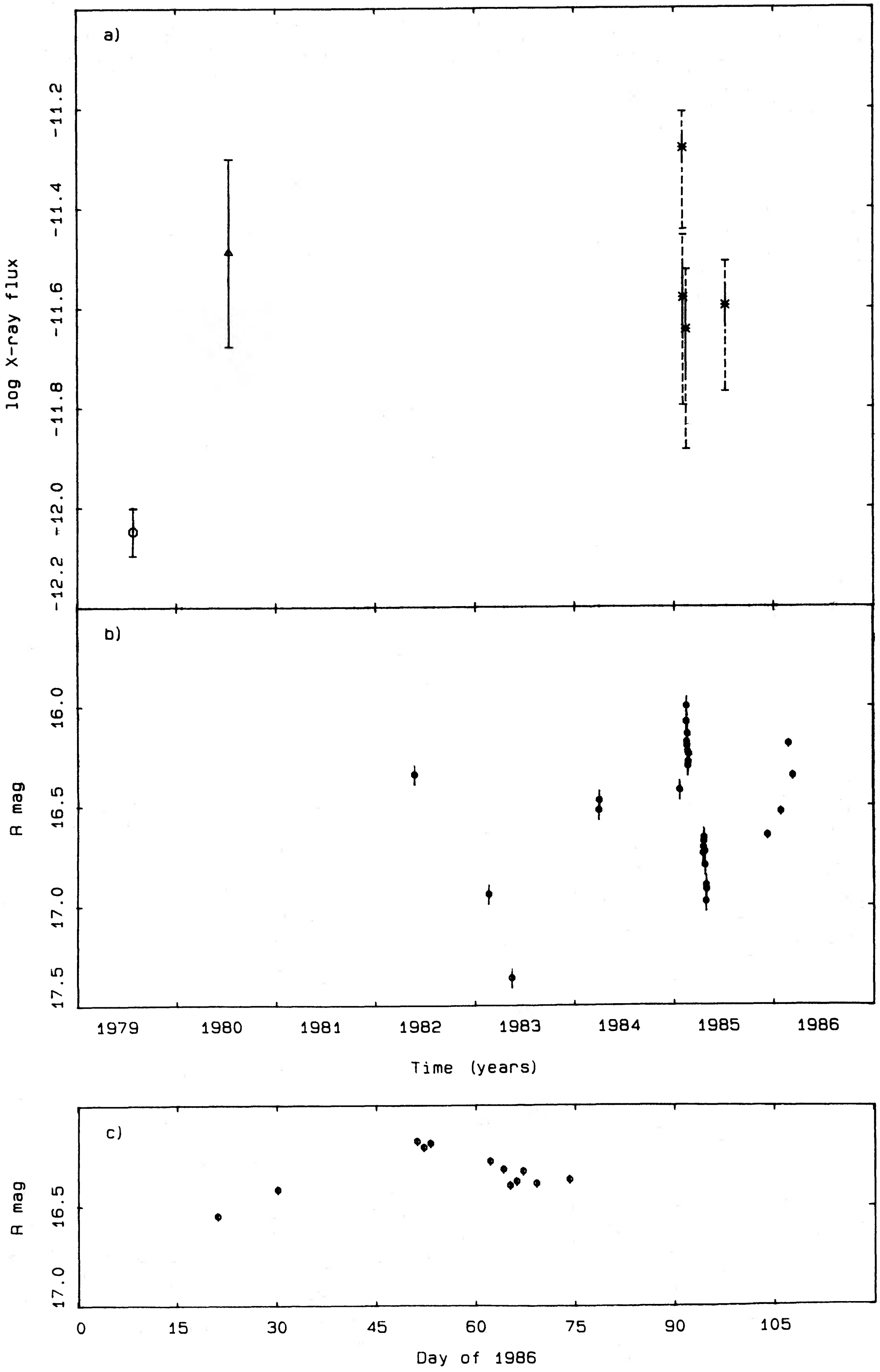

FIG. 5.—X-ray and optical light curves of 1E 1402.3+0416

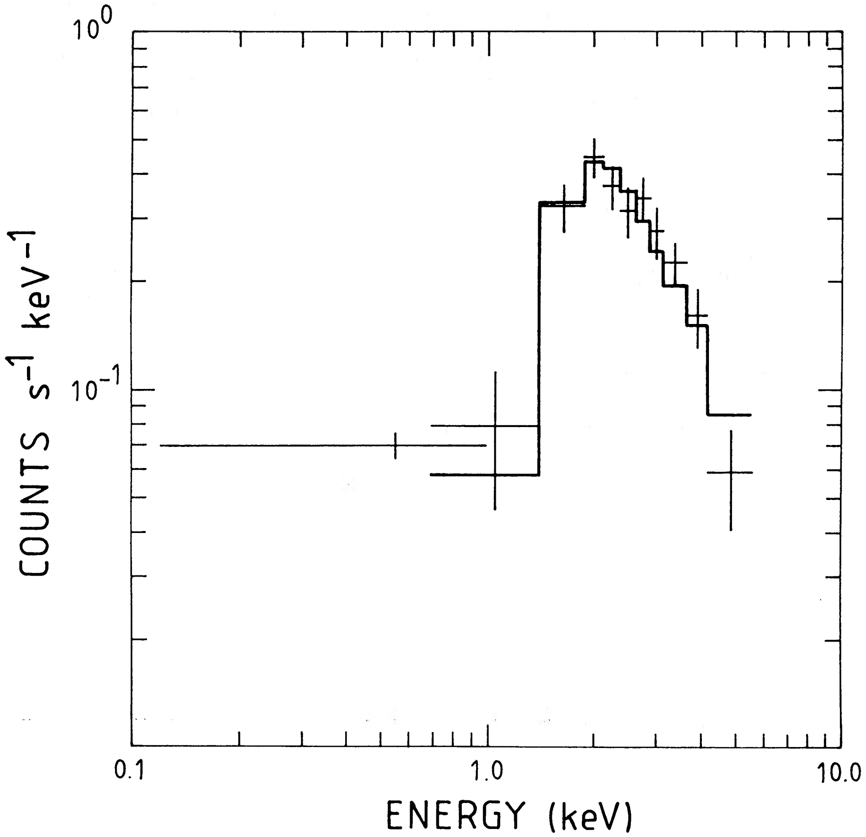

FIG. 6.—Combined ME and LE spectrum of 1E 1415.6+2557

Stark *et al.* 1987). Intrinsic absorption has been found in two other BL Lac objects (PKS 2155−304 and Mrk 501), and has been suggested in three other cases (PKS 0548−322, Mrk 421, and H1218+304) (Urry 1986*a*). However we note that in this case a high value of the inferred column density could be caused by a flattening of the source spectrum near 1 keV. Under the assumption of absorption due solely to material in our Galaxy, a power-law model with energy index 0.5 yields an acceptable χ^2 (similar to that for the best-fitting single power-law model with N_H unrestricted), provided that the spectrum breaks near 1.5–2 keV. Such a flattening has been observed in spectrum of the BL Lac object PKS 0548−322 by Madejski (1985), who reported the detection of a break near 2 keV and by Barr, Giommi, and Maccagni (1987) who found a steepening in the spectrum of the same object above 2–3 keV.

The X-ray flux of 1E 1415.6+2557 as estimated from the IPC observation for a reasonable range of spectral slopes is about a factor of 2 lower than that at the time of the *EXOSAT* observation. However 1E 1415.6+2557 was detected at the edge of the IPC image (see Halpern *et al.* 1986), and for this reason its IPC flux is uncertain. We cannot therefore claim any flux variation between the two observations.

IV. DISCUSSION

a) Time Variability

The optical monitoring of the four MSS BL Lac objects has shown two types of behavior: a night-to-night brightness flickering within a few tenths of a magnitude, and large-amplitude events characterized by brightenings (or dimmings) of ~0.5–1 mag. The only exception is 1E 0317.0+1835, which did not show significant luminosity variations. The most variable object is 1E 1402.3+0416 which brightened twice with time scales of the order of 1 month. This is the only object for which flarelike X-ray intensity variations have been detected nearly contemporaneously with the optical brightening (see Giommi *et al.* 1986). The detected events have shown that the variability time scale in the X-rays is shorter than in the optical and that the rise and decay times do not differ by a large amount, at least at optical wavelengths. The outstanding question about X-ray variability in BL Lac objects is how typical is the behavior observed in 1E 1402.3+0416. Our optical monitoring shows that brightness variations of ~0.5–1 mag occurred also in two other objects: 1E 1235.4+6315 and 1E 1207.9+3945. The former was observed only once by *EXOSAT*, and very little can be said about its X-ray variability, but the latter has been extensively monitored by *EXOSAT* and therefore its luminosity variability can be investigated making a number of assumptions. We have considered the case where the X-ray emission of BL Lac objects can be described by a constant flux plus flare events (similar to those observed in 1E 1402.3+0416; Giommi *et al.* 1986) occurring at time intervals that are Poisson-distributed around a fixed mean rate λ.

A Monte Carlo simulation was performed to produce photon count distributions which were then compared with the observed distributions of counts. The expected count rate at any given instant t can be expressed by (see also Sutherland, Weisskopf, and Kahn 1978):

$$C(t) = K + \sum_{1}^{N}{}_i h * F(t - t_i) ,$$

where

$$F(t - t_i) = \exp\,[(t - t_i)/\tau_r] \qquad \text{if } t < t_i$$

or

$$F(t - t_i) = \exp\,[(t_i - t)/\tau_d] \qquad \text{if } t > t_i\,,$$

K is the constant term, h is the maximum flare intensity, τ_r and τ_d are the rise and decay characteristic times, *ti* are the times corresponding to maximum flare intensity, and N is the total number of flares. For simplicity we have assumed that the rise and decay of X-ray intensity are expoential in shape and that the source spectral index does not vary with luminosity.

The total number of counts during an observation lasting T seconds is:

$$S(t) = \int_t^{t+T} C(t) * dt\,.$$

For each set of parameters, $S(t)$ was calculated for 1000 different values of t. In order to simulate the photon counting statistics, the corresponding $S(t_j)$ ($j = 1$, 1000) were randomized using Poisson distributions with mean equal to $S(t_j)$. Distributions of simulated source counts were then constructed and compared with the actually measured distribution, using a standard Kolmogorov-Smirnov (K-S) test. For each value of h, τ_r, and τ_d, the mean rate of occurrence λ was increased until it reached a value $\lambda_{\rm crit}$ such that the K-S test gave a probability of 1% or less that the simulated and observed distributions come from the same parent distribution. Results are summarized in Table 3 where the values of $1/\lambda_{\rm crit}$ (in units of days) are listed for different values of h and τ_d. In that table, h is given in percentage of the constant flux K. From these results we see that the observed distribution of counts from 1E 1207.9 + 3945 is still consistent with the simulated one if the source brightens by a factor of 2 with a decay time of the order of 1 day, even if the flares occur every 4–5 days on average. If the decay time of the events is of the order of 1 week, the rate of occurrence must be less than one event per month on average. The fact that variations in the optical brightness have been observed in 1E 1207.9 + 3945 while nothing similar has been detected in X-rays could be due to the different time scales of the events (shorter for shorter wavelengths) as observed in 1E 1402.3 + 0416. Events with shorter time scales in the X-rays than in the optical could well be a common feature of X-ray–selected BL Lac objects, as it is for other BL Lac objects (e.g., Urry 1986*b*).

Our simulation shows that, contrary to what our data seem to suggest at first sight, 1E 1207.9 + 3945 could still be a source which undergoes frequent large-amplitude X-ray flux variations with time scales of the order of a few days or shorter. The activity observed in the optical band might be the consequence of these X-ray events. The X-ray variability model assumed can be better investigated with long and continuous observations, rather than by frequent and short ones.

TABLE 4

RESULTS OF MONTE CARLO SIMULATION

A. $\tau_r = \tau_d$

τ_d	h 50%	100%	200%	500%
0.3	0.7	1.3	1.9	2.9
1.0	2.5	4.1	5.9	9.5
10.0	21.	38.	64.	89.

B. $\tau_r = \frac{1}{2}\tau_d$

τ_d	h 50%	100%	200%	500%
0.3	0.3	0.8	1.2	1.8
1.0	1.7	2.9	4.7	6.5
10.0	18.	28.	42.	70.

NOTE.—Maximum average time separation between bursts ($1/\lambda_{\rm crit}$) is tabulated for different values of burst intensity (h) and characteristic decay time (τ_d). Table 4A refers to the case where rise time (τ_r) is equal to decay time, and Table 4B refers to the case where decay time is twice as long as rise time. h is given in percentage of the constant flux, ($1/\lambda_{\rm crit}$); τ_r and τ_d are in units of days.

b) *Energy Spectra*

The advent of *EXOSAT* and the improved knowledge of the instrumental characteristics of the *Einstein* detectors have made available several spectral measurements of BL Lac objects. The energy range and the accuracy of the measurements are quite different. Published results indicate that the X-ray continua of BL Lac objects are well represented by a power-law spectrum with a variety of spectral indices in different energy ranges (see, for example, Urry, Mushotzky, and Holt 1986). Data collected with the *HEAO 1* and *Einstein* satellites suggest that in some cases BL Lac spectra show two components, a steep component at low energy and a flat one at high energy. We have measured the 2–6 keV spectrum of two of the four MSS BL Lac objects, and we have found that the energy slope α is $\gtrsim 1$. The other X-ray–selected BL Lac object, 1E 1415.6 + 2557, also has a steep X-ray spectrum, with an energy index of 2. For all objects, our data do not show any evidence of hard excess out to 8 keV.

Among the four X-ray selected BL Lac objects found in the *HEAO-1* A2 all-sky survey (Piccinotti *et al.* 1982) and included in the sample studied by Stocke *et al.* (1985), PKS 2155 − 304 shows a 2–10 keV energy spectral index α which varies from 1.4 to 1.8 depending on the intensity state (Morini *et al.* 1986). At lower energies (0.6–4.5 keV) Urry, Mushotzky, and Holt (1986) find $\alpha = 1.45$ and $\alpha = 1.56$ from *Einstein* Solid State Spectrometer observations of the same object. Although energy slopes of about 1.5 are common among BL Lac objects, there are examples of harder spectra. PKS 0548 − 322 has shown energy slopes of 1 or flatter and variable in time (Maccagni, Maccacaro, and Tarenghi 1983; Urry, Mushotzky, and Holt 1986). Mrk 501 also shows variability in its spectral index (Urry, Mushotzky, and Holt 1986), with a preference for values above 1.

White, Fabian, and Mushotzky (1984) have suggested that the observed steep X-ray spectra of BL Lac objects arise due to the reprocessing of gamma rays and associated soft photon "pile-up" in a compact, pair-dominated plasma. Both recent (Zdziarsky and Lightman 1985) and less recent (Bonometto and Rees 1971) models of compact sources take into account the effect of the thermalization of photons produced via pair production interaction in the presence of injection mechanisms providing high-energy nonthermal electrons (see, for example, Kazanas 1984). Two cases have been considered: (1) the plasma is optically thick to photons producing the pairs; (2) the plasma is optically thin. Zdziarsky and Lightman (1985) have found that for compactness parameters $L_x/R =$

10^{27}–10^{30} ergs s^{-1} cm^{-1}, the optical depth is less than 1 and the ensuing X-ray spectrum is characterized by an energy slope which ranges from 0.5 to 0.9. Steeper spectra can be obtained for higher compactness parameters, as shown by Bonometto and Rees (1971) who considered the optically thick case. Although the situation is complicated by the assumption on the electron injection spectrum, it seems that, in the framework of these models, X-ray energy spectral slopes greater than 1 are most easily obtained for compactness parameters greater than 10^{30} ergs s^{-1} cm^{-1}. A problem here is that a pair-dominated source is super-Eddington (Svensson 1984), and some means of confining the pairs (e.g., magnetic fields) may be needed to avoid driving off a pair wind. However, Mosalik and Sikora (1986) have constructed a model where the pairs annihilate before escaping from the source, producing discrete hard X-ray flares not unlike that seen in 1E 1402.4+0416. Given the high X-ray luminosity of BL Lac objects (of the order of 10^{45} ergs s^{-1}), a linear source dimension of less than 10^{15} cm is required to obtain the desired compactness parameter. The Thomson optical depth due to pairs is $\tau \gtrsim l^{1/2}$ (where $l = (\sigma_T/m_e c^3)(L_x/R)$ is the dimensionless compactness parameter; see Guilbert, Fabian, and Rees 1983). Thus the Thomson scattering optical depth would be $\tau > 1$ and if the source luminosity is lower than the classical Eddington luminosity, the photon random walk time out of the emitting region would be in the range 3×10^4–2×10^5 s. Variability in this time scale has recently been reported in several objects (e.g., 1E 1402.3+0416, Giommi *et al.* 1986; PKS 2155−304, Morini *et al.* 1986 and Agrawal, Singh, and Riegler 1986; PKS 0548−322, Agrawal, Singh, and Riegler 1986). Alternatively the steep X-ray spectra we observe simply represent the primary photon spectrum (perhaps the synchrotron spectrum corresponding to a steep electron injection spectrum) with no occurrence of gamma-gamma pair production in these sources.

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