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RAPID X-RAY AND OPTICAL VARIABILITY IN THE X-RAY–SELECTED BL LACERTAE OBJECT 1E 1402.3+0416

PAOLO GIOMMI[1,2] AND PAUL BARR[1]
EXOSAT Observatory, ESOC
ISABELLA M. GIOIA,[3] TOMMASO MACCACARO,[3] AND RUDOLPH SCHILD
Center for Astrophysics
AND
BIANCA GARILLI AND DARIO MACCAGNI
Consiglio Nazionale delle Ricerche, Istituto di Fisica Cosmica
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ABSTRACT

Results from X-ray and optical observations of the X-ray–discovered BL Lac object 1E 1402.3+0416 are reported. The X-ray measurements, carried out with the Channel Multiplier Array (CMA) and Medium Energy experiment (ME) detectors on board *EXOSAT*, revealed a factor of 2 decrease in intensity on a time scale of a few hours. At maximum flux, the source was several times brighter than at the time of the *Einstein* Image Proportional Counter (IPC) discovery observation. The 2–6 keV X-ray spectrum has been determined by the ME experiment. This allows us to compare IPC, HRI, and CMA data and to reveal that the source has also varied by a factor of ~5 over a time scale of years.

Almost contemporaneous optical monitoring shows the source to be at the brightest state seen within the last three years and to be varying, on a time scale of a day.

If the redshift of this object is greater than ~0.2, super-Eddington luminosity or anisotropic emission mechanisms must be invoked.

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

I. INTRODUCTION

1E 1402.3+0416 was the first X-ray source identified as a BL Lac object in the *Einstein* Medium Sensitivity Survey (MSS; Maccacaro *et al.* 1982; Stocke *et al.* 1982). Among the MSS BL Lac objects, 1E 1402.3+0416 shows the highest detected optical polarization (~6%) and the largest brightness fluctuation ($\Delta m \approx 1.5$ mag). Its optical spectrum is completely featureless, and no redshift estimate is therefore available. Its optical and radio properties have been studied in detail and are reported by Stocke *et al.* (1985).

In order to study further the X-ray properties of 1E 1402.3+0416, we have observed this object twice using the European Space Agency's X-ray observatory *EXOSAT*. The CMA at the focus of the Low Energy telescope (LE; 0.05–2.0 keV) and the Medium Energy experiment (ME; 1–6 keV) were used (see Taylor *et al.* 1981 for a description of the instrumentation). In addition, nearly simultaneous optical monitoring of this source was obtained. In § II we report the detection of strong X-ray variability over a short time scale (~6 hr) and discuss the X-ray spectrum obtained with the ME when the source was at maximum intensity. This, combined with the recent reprocessing (see Harnden *et al.* 1984 for details) of the IPC observation which led to the discovery of this BL Lac object, enables a meaningful comparison between *EXOSAT* and *Einstein* measurements, thus providing a sampling of the X-ray light curve of this object over a period of six years. In § III the results of the optical monitoring are presented. A brief discussion of the results from these observations, with particular emphasis on the implication of the detected variability on emission models, is given in § IV.

Throughout this paper, $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$ have been used.

[1] Affiliated with Astrophysics Division, Space Science Department of ESA.
[2] On leave of absence from CNR, Istituto di Fisica Cosmica, Milano, Italy.
[3] On leave of absence from CNR, Istituto di Radioastronomia, Bologna, Italy.

II. X-RAY OBSERVATIONS

a) *EXOSAT*

The first *EXOSAT* observation of 1E 1402.3+0416 was performed on 1985 January 31. The source was detected with both the LE and ME experiments. The LE observation was carried out using alternatively the thin Lexan and the Al/Par filters.[4] The thin Lexan filter was primarily used to monitor the source intensity, and the Al/Par filter was used to obtain the additional data necessary to derive broad-band spectral information in the soft X-ray band.

As shown in Figure 1*a*, a decrease of a factor of ~2 in flux occurred between the second and third Lexan exposures, which were separated in time by ~6 hr. A similar intensity decrease was also indicated by the Al/Par data (Fig. 1*b*).

1E 1402.3+0416 was detected by the ME experiment as a faint source (~0.15 c/s) during the first part of the observation when the CMA count rate was high. The ME light curve, obtained by binning the data into 2 hr intervals, shows that the flux decrease is also seen in this instrument (see Fig. 1*c*).

[4] The *EXOSAT* filters are sensitive between 0.02 and 2.5 keV, approximately. The thin lexan filter has an effective area 1.9 times that of the Al/Par filter and provides maximum throughput in the whole energy range. Fifty-five per cent of its effective area is between 0.02 keV and the carbon edge at 0.28 keV. In this same energy range the Al/Par filter has 35% of its effective area (21% between 0.02 and 0.09 keV).

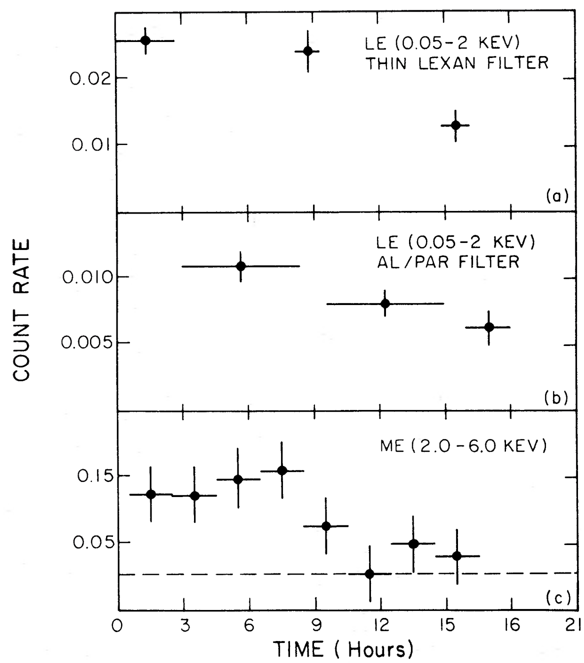

FIG. 1.—Short-term X-ray light curve of 1E 1402.3+0416 as measured by the CMA with Lexan filter (*a*), with Al/Par filter (*b*), and by the ME (*c*) experiments on board the *EXOSAT* Observatory. Time is in hours from the beginning of the observation.

During the observation, the ME background remained stable, and an accurate background subtraction was therefore possible. Using only the data collected during the first 8 hr of the observation, when the source was brighter, we have fitted the net count distribution (in the 2–6 keV band) to a power-law spectrum of the form $dN = KE^{-\Gamma}dE$. We have obtained a best-fit value for the photon index Γ of 2.6 with associated statistical errors of $+0.3/-0.1$ and minimum χ^2 of 17.1 for 10 degrees of freedom. This slope is consistent with the ratio between the count rates in the Lexan and Al/Par exposures for a hydrogen column density of $\sim 2 \times 10^{20}$ $^{\mathrm{cm}^{-2}}$; i.e., equal to the amount found in our own Galaxy in the direction of 1E 1402.3+0416 (Stark *et al.* 1986).

A second *EXOSAT* observation of this source, lasting 9854 seconds on 1985 February 6, was performed to extend the monitoring to time scales of the order of a few days. On this occasion only the thin Lexan filter was used. The source was detected with a count rate of $(9.4 \pm 1.3) \times 10^{-3}$ c/s, slightly lower than at the end of the first observation (see Fig. 2*a*).

b) *Einstein*

Two *Einstein* observations of 1E 1402.3+0416 are available: the IPC image which led to the discovery of this BL Lac object and a subsequent HRI exposure. These two observations were taken on 1979 July 23 and on 1980 July 10 for durations of 9795 and 3016 s, respectively. A direct comparison between the X-ray fluxes measured by instruments sensitive to different energy bands, like the *Einstein* IPC and HRI and the *EXOSAT* CMA, is uncertain unless the intrinsic energy spectrum is known. In the case of 1E 1402.3+0416, the determination of the spectral index from the *EXOSAT* ME data allows direct comparison of X-ray flux measurements obtained by different instruments over a period of several years.

Assuming a constant source spectrum, we have recomputed the X-ray flux of this source from the *Einstein* observations. A photon spectral index of 2.6 and a hydrogen column density of 2×10^{20} cm^{-2} give a flux of 8.8×10^{-13} ergs cm^{-2} s^{-1} from the IPC observation and a flux of 3.3×10^{-12} ergs cm^{-2} s^{-1} from the HRI observation (fluxes have been corrected for galactic absorption and have been computed in the 0.3–3.5 keV band).[5] This indicates that 1E 1402.3+0416 increase its flux by approximately a factor of 4 over the interval of 1 yr between the *Einstein* observations. A further brightening is indicated by the *EXOSAT* measurements, which yield a flux of

[5] Determination of the flux from an HRI observation is particularly sensitive to the assumed spectral parameters. If we assume that at the time of the HRI observation 1E 1402.3+0416 was characterized by a different energy spectrum than that measured by *EXOSAT*, we obtain a different flux estimate and consequently a different variability pattern. We have indicated in Fig. 3*a* the flux that would have resulted from the HRI observation should the spectrum of 1E 1402.3+0416 have been characterized by a flatter ($\Gamma = 2.0$) or steeper ($\Gamma = 3.2$) slope.

TABLE 1

SUMMARY OF THE X-RAY FLUX MEASUREMENTS OF 1E 1402.3+0416

Instrument	Date	Flux (0.3–3.5 keV) 10^{-12} ergs cm^{-2} s^{-1}	Filter
Einstein IPC..........	1979 Jul 23	0.9 ± 0.06	...
Einstein HRI	1980 Jul 10	3.3 ± 0.3	...
EXOSAT CMA......	1985 Jan 31.06	4.9 ± 0.4	Thin Lexan
EXOSAT CMA......	1985 Jan 31.23	4.7 ± 0.4	Al/Par
EXOSAT CMA......	1985 Jan 31.36	4.5 ± 0.6	Thin Lexan
EXOSAT CMA......	1985 Jan 31.51	3.3 ± 0.3	Al/Par
EXOSAT CMA......	1985 Jan 31.65	2.5 ± 0.4	Thin Lexan
EXOSAT CMA......	1985 Jan 31.71	2.8 ± 0.5	Al/Par
EXOSAT CMA......	1985 Feb 6	1.9 ± 0.2	Thin Lexan

TABLE 2

OPTICAL MONITORING OF 1E 1402.3+0416

Date (1985)	*R* Mag
Jan 18.......................	16.42
Feb 11	16.08
Feb 12	16.00
Feb 13	16.18
Feb 14	16.20
Feb 15	16.14
Feb 16	16.23
Feb 17	16.30
Feb 18	16.28
Feb 20	16.24
Apr 13	16.74
Apr 14	16.71
Apr 15	16.68
Apr 16	16.66
Apr 19	16.73
Apr 20	16.80
Apr 23	16.98
Apr 24	16.90
Apr 25	16.92

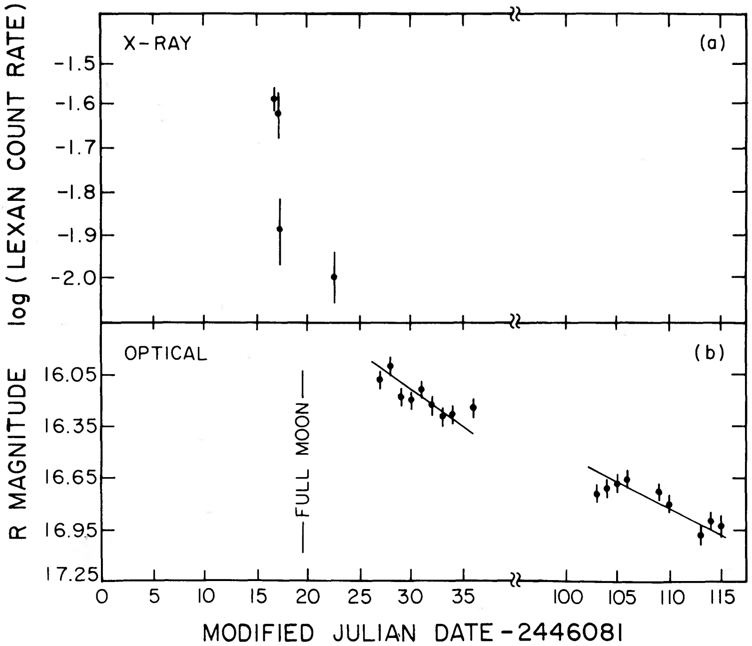

FIG. 2

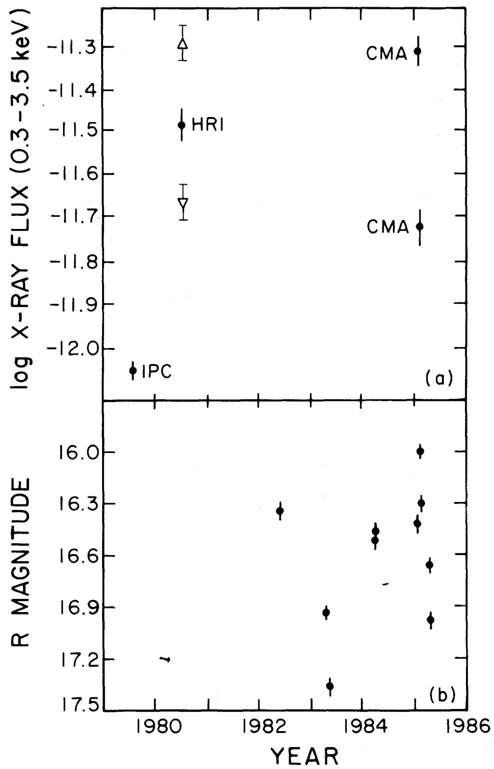

FIG. 3

FIG. 2.—Short-term X-ray (*EXOSAT* Lexan filter) (*a*) and optical (*R* magnitude) (*b*) variability of 1E 1402.3+0416 (*see text for details*). Note that the vertical scale has been chosen in such a way that equal variations are of equal amplitude in both bands.

FIG. 3.—Long-term X-ray (0.3–3.5 keV) (*a*) and optical (*R* magnitude) (*b*) variability of 1E 1402.3+0416. For the period 1985 February and April, for the sake of clarity only the maximum and minimum magnitudes have been plotted. As in Fig. 2, the vertical scale has been chosen in such a way that equal variations are of equal amplitude in both bands. The two open triangles in the upper panel represent the flux derived from the HRI observation under the assumption of a steeper (∇) and flatter (Δ) power-law slope than observed by *EXOSAT*. See text for details.

4.9×10^{-12} ergs cm^{-2} s^{-1} in the same 0.3–3.5 keV band at the beginning of the first *EXOSAT* observation. In the last *EXOSAT* exposure the flux had decreased to 1.9×10^{-12} ergs cm^{-2} s^{-1}, a value intermediate between the two *Einstein* observations.[6]

All the available X-ray flux measurements of 1E 1402.3+0416 are shown in Figure 3*a* and summarized in Table 1.

III. OPTICAL OBSERVATIONS

Optical observations of the BL Lac object were made in 1985 on January 18, February 11–20, and April 13–25. A surrounding group of field stars were used as brightness standards. No simultaneous optical and X-ray observations could be arranged because the latter were obtained during the bright-moon period. All optical observations were made with the RCA CCD camera (Geary and Kent 1981) on the 61 cm telescope of the Whipple Observatory, with a broad red-sensitive filter approximating the Johnson (1966) *R* band. Our minimum nightly exposure was a single 10 minute integration, and most nights a second 10 minute integration was obtained with the telescope moved slightly between integrations. A finding chart with identifications and photometry of field standards is given in Stocke *et al.* (1985). Standard CCD reduction procedures were followed, and we find from repeated observations on individual nights that the measurement error is 0.02 mag. In addition, the zero point of our magnitude scale for the field standards is uncertain by 0.03 mag. All magnitudes reported here are on the Johnson *R* system and are listed in Table 2.

The results of our optical monitoring and of the *EXOSAT*/*Einstein* observations are shown in Figures 2 and 3. Previous data points reported by Stocke *et al.* (1985) are also included. Inspection of these figures shows that at about the time of the *EXOSAT* observation the source had the greatest brightness seen during the three-year history of optical monitoring. 1E 1402.3+0416 subsequently faded by 1 mag over the following 80 days.

To obtain an estimate of the *R* magnitude at the time of the X-ray observation, we performed a linear regression of the

[6] The factor 10 increase between IPC and CMA measurements reported by GIOMMI and Barr (1985) was based upon the assumption of a power-law spectrum with photon index $\Gamma = 1.5$ and $N_H = 3 \times 10^{20}$ cm^{-2}, as originally used to compute the IPC flux by Maccacaro *et al.* (1982).

optical magnitudes against observation date (see Fig. 2*b*). A small extrapolation of the fit gives us a value of $R = 15.81$ for February 6, the date of the second *EXOSAT* observation. Extrapolating further, to the time of the first *EXOSAT* observation on 1985 January 31, gives $R = 15.56$.

Residuals from the best-fitting line give nightly deviations from the long term trend of 0.06 mag. This value is twice the mean deviation due to measurement errors of 0.03 mag, indicating that night-to-night brightness fluctuations (flickering) around the BL Lac object long-term brightness changes are of the order of 0.05 mag.

In a similar way, we have fitted a linear slope to the 1985 April data. The mean deviation from the best-fitting line is 0.05 mag, again indicating a flickering of 0.05 mag around the longer trend.

Finally we note that in February 1E 1402.3+0416 was decreasing its optical flux at a faster rate than in April when it was a factor of 2 fainter.

IV. DISCUSSION

BL Lac objects are known to show strong time variability at virtually all wavelengths. In the X-rays, flux or spectral variations, or both, on time scales ranging from several years to hours have been reported by several authors (see, among others, Worrall *et al.* 1981; Maccagni, Maccacaro, and Tarenghi 1983; Agrawal, Singh, and Riegler 1983; Snyder *et al.* 1980). The ~6 hr variation in 1E 1402.3+0416 discussed here, although not so extreme as the ~30 s variation of H0323+022 (Feigelson *et al.* 1986) is one of the fastest reported yet.

In the optical, 1E 1402.3+0416 has brightened by ~1 mag on a time scale of 10 months. Between 1985 January 18 and February 11, during the *EXOSAT* observations, a brightening of 0.5 mag was seen. The daily monitoring after that epoch shows a rather regular decrease. It is possible that the time behavior of this BL Lac is different in the X-rays and in the optical, both in the degree of variability and in the decay time scale, although the lack of simultaneous measurements leaves room for different interpretations. A faster and larger amplitude variability in the X-rays with respect to the optical is, however, easily accommodated in the framework of a model like Marscher's (1980), which would also predict a delay in the bursting activity as the wavelength increases. Under the hypothesis that the half-intensity scale of the optical decay is 1 month, the dimension of the emission region would be 8×10^{16} cm, while the X-ray source should have a dimension of only 7×10^{14} cm.

For a source radiating isotropically at the Eddington limit and converting matter into energy by accretion onto a massive central object, we have (Cavallo and Rees 1978; Fabian 1979):

$$\Delta L < 2 \times 10^{42} \eta \Delta t \text{ ergs s}^{-1} ,$$

where η is the conversion efficiency which is likely to be $\lesssim 0.1$ and certainly less than 0.4. In the case of 1E 1402.3+0416, $\Delta t \approx 2.2 \times 10^4$ s and the maximum allowed luminosity variation on this time scale and over the whole observed energy range (0.05–6 keV) is $\sim 4.3 \times 10^{46} \eta$ ergs s^{-1}. This, combined with the observed flux in the same energy band after correction for galactic absorption, corresponds to a redshift in the range 0.1–0.2.

This value for the redshift would be consistent with the interpretation of the broad "hump" at 4900 Å with Ca II H and K (Stocke *et al.* 1985). However, as discussed by Stocke *et al.* (1985), the stellar appearance of the BL Lac on deep CCD frames suggests a redshift of ~0.5 or higher. If the source is indeed at such a redshift, then the observed ΔL in the 0.05–6 keV range would be of the order of 1×10^{47} ergs s^{-1} and special geometries (e.g., beamed emission) or super-Eddington regimes are required. Under the assumption that the emission occurs in a relativistic jet, a kinematic Doppler factor $\delta \gtrsim 2$ would reconcile a high redshift with the limit on the luminosity variation set by the efficiency of conversion of matter into energy.

A thorough discussion of the overall frequency spectrum (see Fig. 4) would require simultaneous measurements and possibly IR and UV observations. However, a few features are apparent. In the radio the spectrum has an energy slope of ~1, steeper than for most radio-selected BL Lac objects (Stein, O'Dell, and Strittmatter 1976). The spectrum must then flatten at 10^{13} Hz in order to connect smoothly with the optical spectrum, which is flat between the R and V passbands and then steepens toward the blue. Finally it assumes a slope of 1.6 (energy index) in the X-rays. This behavior is suggestive of two components in the source: a rather large and extended one emitting in the radio and a much smaller region, emitting probably synchrotron radiation, in the optical through the X-rays. This last component could well be beamed emission if the redshift of this object is larger than ~0.2.

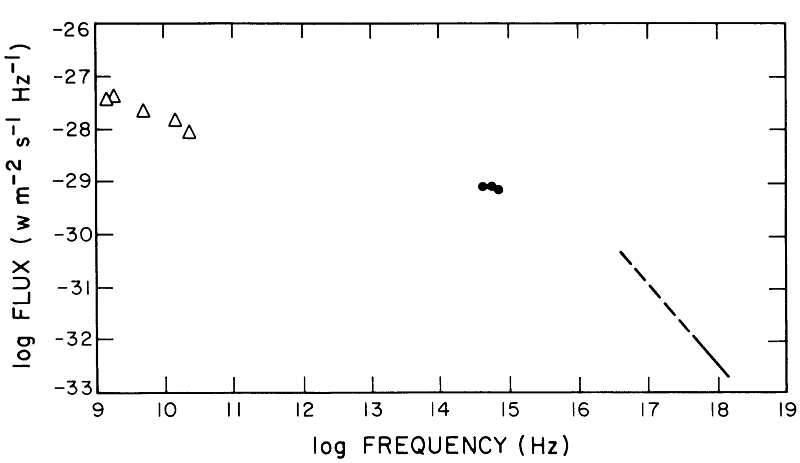

FIG. 4.—Overall energy spectrum of 1E 1402.3+0416. Radio, optical, and X-ray observations are not simultaneous

At present, a VLA observation at 6 cm, in the A-configuration (our data, unpublished) sets an upper limit of ~0″.2 to the size of the radio-emitting region, which corresponds to a physical size of ~900 pc at a redshift of 0.2 and to 1600 pc at a redshift of 0.5. Clearly a VLBI measurement would be necessary to resolve spatially the radio source.

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P. Barr and P. Giommi: *EXOSAT* Observatory, ESOC, R. Bosch Strasse 5, 61 Darmstadt, F.R.G.

B. Garilli and D. Maccagni: CNR, Istituto di Fisica, via Bassini 15, 20133 Milano, Italy

I. M. Gioia, T. Maccacaro, and R. Schild: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138