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ROSAT OBSERVATIONS OF THE BLAZAR PKS 0537−441

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ABSTRACT

PKS 0537−441, an object with properties intermediate between BL Lacertae objects and OVVs, was observed with *ROSAT* in 1991 April. The X-ray state $F_{1\,\mathrm{keV}} = 0.79 \pm 0.05$ μJy is brighter than those detected by the *Einstein Observatory* (1979–1980), and *EXOSAT* (1985) satellites, while the spectral slope $\alpha_{\mathrm{ph}} = 2.1 \pm 0.4$ is steeper. The hydrogen column density $N_{\mathrm{H}} = (3.0 \pm 1.3) \times 10^{20}$ cm^{-2} is consistent with that deduced from 21 cm observations. Optical spectrophotometry of 1991 February indicates a moderately high state of the source. The observations are discussed also in the light of the newly discovered gamma-ray emission.

Subject headings: BL Lacertae objects: individual (PKS 0537−441) — X-rays: galaxies

1. INTRODUCTION

PKS 0537−441 is a transition object between the class of BL Lacertae objects, characterized by a strongly variable, polarized and featureless nonthermal continuum, and that of Violently Variable and Highly Polarized Quasars. When the continuum is weak, a broad Mg II (2800 Å) emission is clearly present, while in high states the line is washed out (Falomo et al. 1989 and references therein). Repeated multifrequency observations of the object from the near-IR to the X-ray band (Maraschi et al. 1985; Tanzi et al. 1986) showed the occurrence of quasi-simultaneous flares at IR, optical, and X-ray frequencies. The radio to optical continuum of the object must be relativistically enhanced in order to reconcile the rapid variability with the high (apparent) luminosity (Ghisellini, Maraschi, & Treves 1985). This may be due to bulk relativistic motion of the emitting plasma or to gravitational lensing. Observational indications in favor of the latter hypothesis were reported by Stickel, Fried, & Kühr (1988), but not confirmed by Falomo, Melnick, & Tanzi (1992).

The source was recently detected in gamma rays by the EGRET experiment on board the *Gamma-Ray Observatory*. The flux above 100 MeV as measured in 1991 July–August was $(1\text{–}3) \times 10^{-7}$ ph cm^{-2} s^{-1} (Michelson et al. 1992).

Here we report on X-ray observations of the source obtained with *ROSAT* in 1991 April, together with a re-examination of the previous *EXOSAT* data. Preliminary results were presented at a conference (Treves et al. 1992). The observations are part of a wider program of X-ray observations of blazars aimed at understanding the X-ray emission mechanism(s) in objects with and without emission lines.

2. *ROSAT* OBSERVATIONS

PKS 0537−441 was observed with the *ROSAT* Position Sensitive Proportional Counter (PSPC) for a total of 1417 s. The source photons were extracted from a circle of 2′ radius around the centroid of the photon distribution; a sample of the background was derived from a ring around the source with inner and outer radii of 5′ and 12′, respectively. The mean source count rate, corrected for vignetting effects is 0.345 ± 0.067 counts s^{-1}. The corresponding background count rate scaled to the same extraction area is 0.016 ± 0.002 counts s^{-1}. A light curve with a binning of 100 s is reported in Figure 1. The wobbling of the pointing direction with a period of 400 s introduces spurious variability in on-axis sources: the "waving" structure visible in the light curve is likely due to such effects, and no indication of source variability is found.

The count spectrum (500 photons) accumulated over the entire exposure time was then rebinned in order to get a signal-to-noise ratio larger than 5 σ in all bins. This was fitted with the simple model of an absorbed power law, the free parameters being the column density (the Morrison & McCammon [1983] cross sections have been used), the photon index, and the normalization. We obtained a photon spectral index $\alpha_{\mathrm{ph}} = 2.1 \pm 0.4$ and a column density of $N_{\mathrm{H}} = 3.0 \pm 1.3 \times 10^{20}$ cm^{-2} (see Table 1). Figure 2 shows the deconvolved data, together with the best fit and confidence contours. Signal was detected over the whole PSPC energy range (0.1–2.4 keV), and the fit is satisfactory. The value for the hydrogen column density is consistent with that deduced from 21 cm observations, $N_{\mathrm{H}} = 4 \times 10^{20}$ cm^{-2} (Heiles & Cleary 1979).

3. PREVIOUS X-RAY OBSERVATIONS

3.1. *Einstein Observations*

The source was observed at three epochs with the *Einstein Observatory* (Maraschi et al. 1985). The 1 keV fluxes, estimated assuming $\alpha_{\mathrm{ph}} \sim 1.5$ and $N_{\mathrm{H}} \sim 4 \times 10^{20}$ cm^{-2}, are reported in Table 2 for the various epochs. Substantial X-ray variability is inferred, the flux observed by *ROSAT* being the highest ever observed. Because of the better energy resolution the present observations constrain the spectral shape more effectively than the *Einstein* ones, which were based on 300 photons. The photon index as from the *Einstein* observations, for a fixed value of $N_{\mathrm{H}} = 4 \times 10^{20}$ cm^{-2}, was $\alpha_{\mathrm{ph}} = 1.55 \pm 0.4$, only marginally compatible with the *ROSAT* value for the same absorption column density, $\alpha_{\mathrm{ph}} = 2.37 \pm 0.12$ (see Fig. 2).

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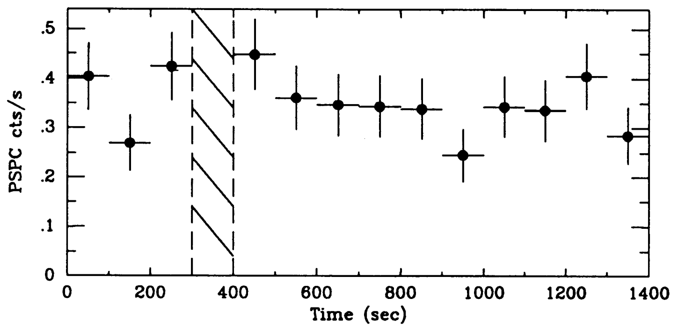

FIG. 1.—*ROSAT* light curve of PKS 0537−441. First fraction: 1991 April 10, UT 09.00. Second fraction: 1991 April 16, UT 14.03.

TABLE 1

PSPC BEST FIT OF PKS 0537−441

Parameter	Value
α_{ph}	2.1 ± 0.4
N_H	$(3.0 \pm 1.3) \times 10^{20}$ cm^{-2}
χ^2/(d.o.f.)	1.06/14
Flux (0.1–2.4) keV	$(7.4 \pm 2.62) \times 10^{-12}$ ergs cm^{-2} s^{-1}
Flux at 1 keV	0.79 ± 0.05 μJy

3.2. *EXOSAT Observations*

The source was observed at two epochs with *EXOSAT* (Tanzi et al. 1986) during a moderately active optical state. The discovery of the gamma-ray emission from the source mentioned above led us to reconsider the *EXOSAT* observations. In fact, since the source was very weak in the Low-Energy (LE) experiment (0.05–2 keV), in our previous paper (Tanzi et al. 1986) we did not explore the response of the Medium Energy (ME) experiment (1–20 keV).

The two *EXOSAT* observations were reexamined first using the satellite data base and then proceeding to a new signal extraction from the data of the Final Observation Tape (FOT). At the time of the first *EXOSAT* observation, when the LE flux was highest (see Table 2), no evidence of signal in the ME detector was found at the 3 σ confidence level. However, during the second *EXOSAT* observation, when the LE intensity had decreased by 30%, a signal was detected in the ME in the 1.5–7 keV interval. We have carefully looked at for possible spurious effects (e.g., solar activity) and found none. The possibility of the burst of a foreground transient X-ray source was also discarded on the basis of the absence of counterpart in the LE image.

We have combined the ME spectrum (19 bins) with the LE count rate and fitted with an absorbed power law and N_H fixed at the galactic value. This yields $\alpha_{ph} = 1.26^{+0.24}_{-0.31}$, $\chi^2 = 8$ for 18 degrees of freedom (d.o.f.). The fit of the ME spectrum is consistent with that of the LE+ME one. Assuming N_H as a free parameter one has $\alpha_{ph} = 1.00^{+0.76}_{-0.44}$, $N_H = 1.5 \times 10^{20}$ ($\leq 20 \times 10^{20}$), $\chi^2 = 8.4$ for 17 d.o.f., and therefore, indication for a hard energy spectrum. Evidence is also found of a hardening of the spectrum in correspondence to a dimming of the source in the LE band. Figure 3 shows the *EXOSAT* spectrum.

TABLE 2

X-RAY FLUXES OF PKS 0537−441 AT 1 keV

Date	Flux (μJy)	Satellite
1979 Oct 9	0.12 ± 0.03	*Einstein*
1980 Apr 7	0.15 ± 0.016	*Einstein*
1980 Sep 27	0.22 ± 0.019	*Einstein*
1985 Feb 11	0.46 ± 0.08	*EXOSAT*
1985 Feb 24	0.31 ± 0.07	*EXOSAT*
1991 Apr 16	0.79 ± 0.05	*ROSAT*

NOTE.—*Einstein* and *EXOSAT* fluxes are taken from Maraschi et al. 1985 and Tanzi et al. 1986.

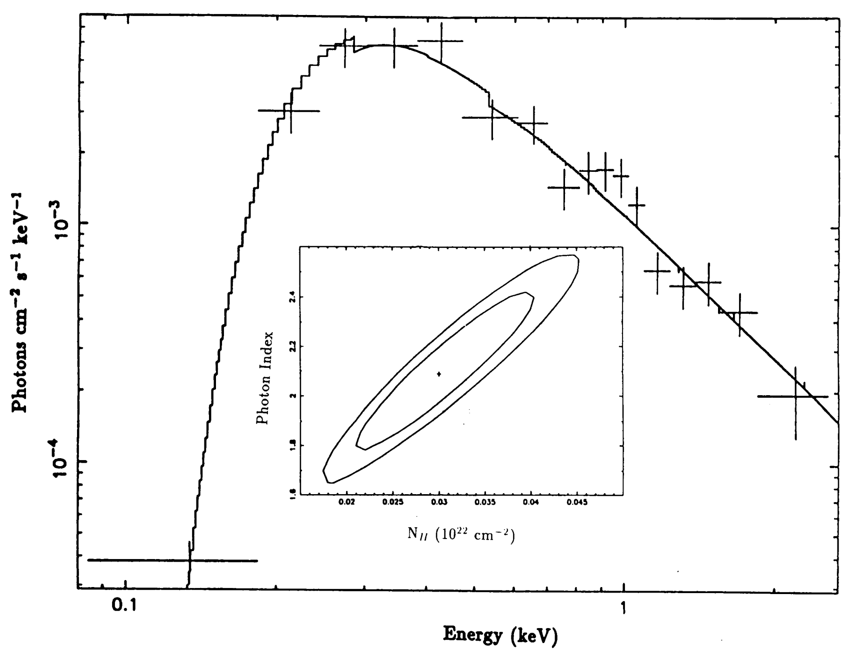

FIG. 2.—*ROSAT* spectrum of PKS 0537−441. The solid curve represents an absorbed power law with the parameters specified in Table 1. Inset: α/N_H contours (68.3% and 90% confidence levels).

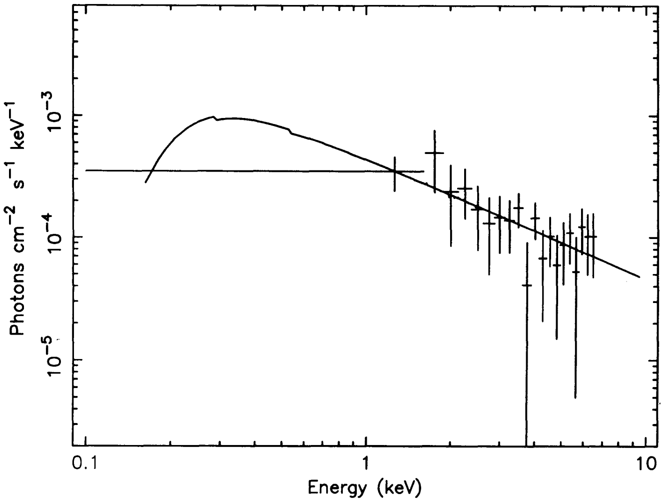

FIG. 3.—*EXOSAT* spectrum of PKS 0537−441 of 1985 February 24. The solid line is an absorbed power law, as given in the text.

The *EXOSAT* spectral index is similar to that obtained with the *Einstein Observatory* and harder than that of *ROSAT*. However, one should keep in mind the different energy intervals covered by the three satellites.

4. OPTICAL OBSERVATIONS

Optical spectrophotometry of the object (see Fig. 4) was secured 2 months before the *ROSAT* observations with the European Southern Observatory 1.5 m telescopes. A low-resolution (FWHM $\approx$ 15 Å) spectrum was obtained with a Boller and Chivens spectrograph and CCD detector. Apart from the weak emission feature of Mg II at 300 Å (E.W. = 2.3 ± 0.4 Å, $I_\lambda = (4 \pm 1) \times 10^{-14}$ ergs cm^{-2} s^{-1}), the spectrum is featureless and can be fitted by a power law $\alpha_{ph} = 2.3 \pm 0.1$. The broad-band magnitudes of the object derived from the spectrum are $B = 16.3$, $V = 15.7$, and $R = 15.3$. Photometric accuracy as derived from observations of several standard stars (Stone 1977) is better than 10%.

From 1984 to 1991 we collected 14 homogeneous spectrophotometric observations of the source ranging from $V = 17.2$ to $V = 15.6$. The latest observation therefore corresponds to a bright state, which could be related to the high X-ray state detected 2 months later. In fact, a brightening up to at least 15.2 over a 2 month period was observed in correspondence with the moderately high X-ray state detected by *EXOSAT* in early 1985 (Tanzi et al. 1986).

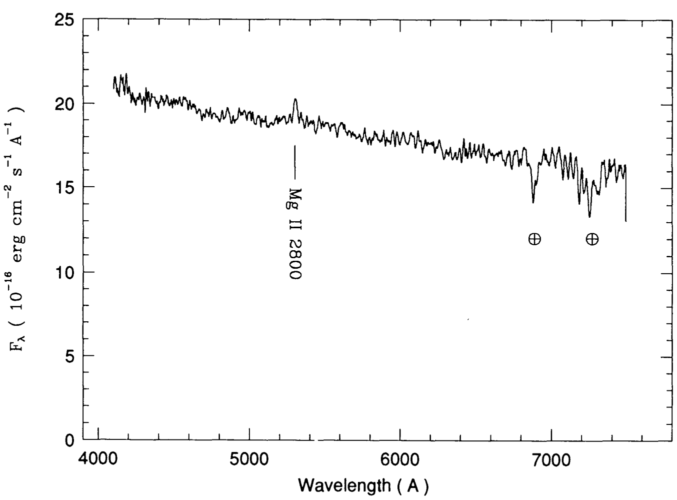

FIG. 4.—Optical spectrophotometry of PKS 0537−441 obtained on 1991 February 12.

5. DISCUSSION

Comparison of the *ROSAT* X-ray spectrum with the *Einstein* and *EXOSAT* observations indicates a substantial variability both in the intensity and spectral shape.

Although our observations are far from exhaustive, it appears that for PKS 0537−441 brighter X-ray states correspond to a softer spectral shape. This spectral behavior is opposite to that found in the *EXOSAT* BL Lacertae sample discussed by Giommi et al. (1990).

The presence of a medium-energy component in the X-ray band in PKS 0537−441 is interesting in view of the recent detection of high-energy gamma rays from this object. In fact, the hard *EXOSAT* state and *Einstein* last observation connect smoothly with the gamma-ray point, while extrapolation of the *ROSAT* spectrum falls largely below the gamma-ray observations.

Although not strictly simultaneous, it is worth comparing the emission in optical, X-ray, and gamma-ray bands measured in 1991 and reported here. In the source system ($z = 0.894$, $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$), one has $\nu L_\nu \sim 10^{47}$, $\sim 10^{46}$, and $\sim 2.5 \times 10^{47}$ ergs s^{-1}, at 2500 Å, 2 keV, 200 MeV, respectively (see Fig. 5). The bolometric power is possibly dominated by the highest frequencies.

We propose to interpret the energy distribution in terms of an inhomogeneous jet model which we have described in some detail in earlier papers (Ghisellini, Maraschi, & Treves 1985; Celotti, Maraschi, & Treves 1991). In short, the model considers a paraboloid plus cone-shaped regions filled with relativistic electrons, the energy distribution of which is a power law. Electron density, magnetic energy density, and maximum electron energy have a power-law dependence on the axial distance. As emission processes, synchrotron, and synchrotron–self-Compton are considered. This model was applied (Ghisellini et al. 1985) to PKS 0537−441 starting from the observations available at the time. It was concluded that while relativistic beaming was needed for the cone region responsible for the radio emission, no beaming was requested for the inner parabolic source producing the X-rays. The

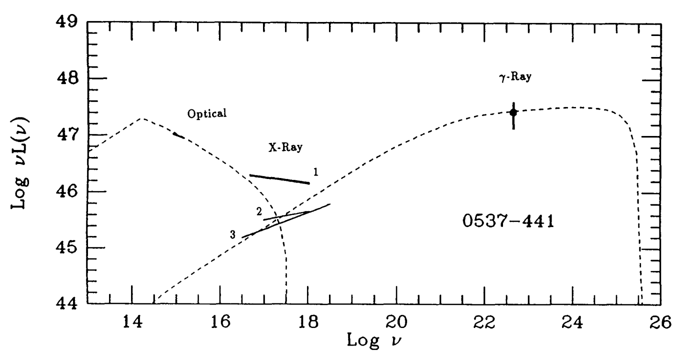

FIG. 5.—Comparison of the 1991 observations (*solid segments*) with the model of Maraschi et al. (1992). The dotted lines represent the synchrotron (*left*) and Compton (*right*) contributions. Labels indicate the X-ray luminosities from the three satellites: 1, *ROSAT*; 2, *Einstein*; 3, *EXOSAT*.

parameter choice adopted then yields a gamma-ray flux which is below by a factor of 10 with respect to the observations. The inhomogeneous jet model was further developed by Ghisellini & Maraschi (1989). It introduced a smooth acceleration of the bulk flow joining the inner weakly beamed region with the outer strongly beamed one. This is now applied to the present data of PSR 0537−441, with the results shown in Figure 5. (For a complete specification of the model parameters, see Maraschi, Ghisellini, & Boccasile 1992). The model is not a best fit of the observations. Note that in the X-ray range both synchrotron and Compton emission contribute, which may explain the observed variability of the X-ray spectral index if the two components vary nonsimultaneously. In fact synchrotron X-rays derive from the innermost part of the jet, while Compton X-rays derive from an intermediate region whose synchrotron emission is in the far-infrared. The same model can account for the 100 MeV gamma-ray emission as Compton from optical UV photons. The derived beaming factor for the gamma-ray emitting region is $\delta = 8$. A similar model (Maraschi, Ghisellini, & Celotti 1992) has been recently applied to explain the broad-band energy distribution and gamma-ray emission of 3C 279 (Hartmann et al. 1992), which are in many respects similar to the case of PKS 0537−44.

In order to better constrain the free parameters of the model one should have simultaneous observations in the various bands. If the model does apply to PKS 0537−441, an immediate consequence would be the expectancy of major variability in the gamma-ray emission, as already observed in 3C 279.

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