Astron. Astrophys. 333, L5–L8 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

*Letter to the Editor*

# The complex 0.1–100 keV X-ray spectrum of PKS 2155-304

**P. Giommi**[1], **F. Fiore**[1,2], **M. Guainazzi**[1], **M. Feroci**[3], **F. Frontera**[4,5], **G. Ghisellini**[6], **P. Grandi**[3], **L. Maraschi**[6], **T. Mineo**[7], **S. Molendi**[8,1], **A. Orr**[9], **S. Piraino**[7], **A. Segreto**[7], **G. Tagliaferri**[6], **and A. Treves**[10]

[1] *BeppoSAX* Science Data Center, ASI, Via Corcolle 19, I-00131 Roma, Italy
[2] Osservatorio Astronomico di Roma, Monteporzio Catone, Italy
[3] Istituto di Astrofisica Spaziale, CNR, Via Enrico Fermi 21, I-00044 Frascati, Italy
[4] Dipartimento di Fisica, Universitá di Ferrara, Via Paradiso 12, I-44100 Ferrara, Italy
[5] Istituto TESRE, CNR, Via Gobetti 101, I-40129 Bologna, Italy
[6] Osservatorio Astronomico di Brera, via Brera 28, I-20121 Milano, Italy
[7] Istituto di Fisica Cosmica ed Applicazioni dell'Informatica, C.N.R. Via Ugo La Malfa 156, Palermo, Italy
[8] Istituto di Fisica Cosmica, CNR, Via Bassini 15, I-20133 Milano, Italy
[9] Space Science Department of ESA, ESTEC, Keplerlaan, Noordwijk, The Netherlands
[10] Universita' di Milano, sede di Como, Via Lucini 3, I-22100 Como, Italy

Received 3 July 1997 / Accepted 24 July 1997

**Abstract.** A long ($> 100,000$ seconds) observation of the bright BL Lac object PKS 2155-304 has been carried out with the Narrow Field Instruments of the *BeppoSAX* satellite as part of the Science Verification Phase. The source was detected between 0.1 and about 100 keV at an intermediate intensity level compared to previous observations. The unique spectral coverage of *BeppoSAX* has allowed us to detect a number of spectral features. Between 0.1 and 10 keV the spectrum can be well described by a convex spectrum with (energy) slope gradually steepening from 1.1 to 1.6. At higher energies evidence for a sharp spectral hardening is found, while in the soft X-rays (0.1–1.0 keV) some evidence for an absorption feature was found. Indication for an emission line at 6.4 keV in the source rest frame is present. Repeated variability of $\approx$ 20–30% around the mean flux is clearly detected on time scales of a few hours. From the symmetry and timescale of the observed variations we derive limits on the magnetic field and on the maximum energy of the emitting particles, implying that PKS 2155-304 should not be bright at TeV energies.

**Key words:** galaxies, active

## 1. Introduction

BL Lac objects are highly variable AGN emitting non-thermal radiation from radio to high energy gamma-rays, in some cases up to TeV energies. The mechanism responsible for the production of radiation over such a wide energy range is believed to be the synchrotron emission followed at higher energies by inverse Compton scattering (e.g. Bregman et al. 1994). PKS 2155-304 is a BL Lac that was discovered in the X-ray band where it is one of the brightest extragalactic sources. Its synchrotron power output peaks at UV frequencies (Giommi, Ansari & Micol 1995) after which a steep, highly variable, continuum follows up to the mid-hard X-ray band where a much flatter component must emerge to explain the gamma ray emission detected by CGRO (Vestrand et al. 1995).

PKS 2155-304 has shown absorption features in the soft X-rays that have been attributed to highly ionized oxygen, possibly moving at relativistic speed toward the observer (Canizares & Kruper 1984, Madejski et al. 1991, 1997). Evidence for other absorption features have also been found at EUV frequencies by Königl et al. (1995).

In this letter we report the results of a long ($>$ 2 days) observation of PKS 2155-305 that was carried out on 20–22 November 1996 as part of the *BeppoSAX* Science Verification Phase (SVP). Here we concentrate on the analysis of the general shape of the energy spectrum and we briefly describe the time variability. A detailed timing analysis and a comprehensive study of the soft X-ray absorption features will be presented in future papers.

## 2. Observations

The *BeppoSAX* X-ray telescopes include one Low Energy Concentrator Spectrometer (LECS, Parmar et al. 1997) sensitive in the 0.1–10 keV band, and three identical Medium Energy Concentrator Spectrometers (MECS, Boella et al. 1997) covering the 1.5–10 keV band. During the *BeppoSAX* SVP PKS 2155-304 was observed for more than 2 days using all the Narrow Field Instruments. The effective exposure time in the MECS was 107,702 seconds. Since at the LECS instrument can only be operated when the spacecraft is in the earth shadow the expo-

*Send offprint requests to*: P. Giommi

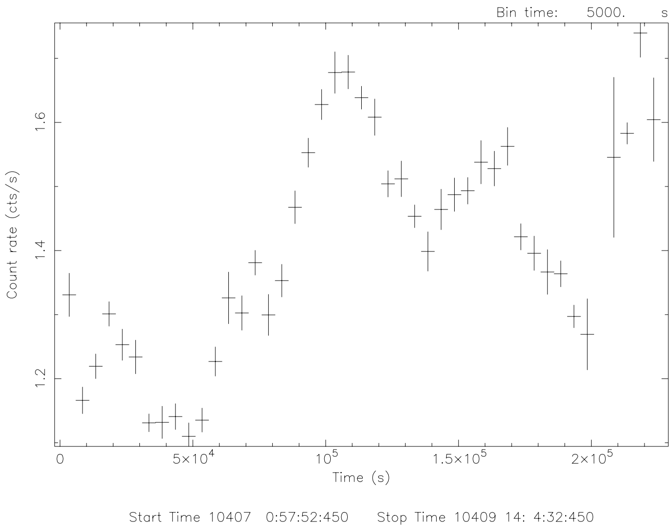


**Fig. 1.** The 1.5–10 keV MECS lightcurve of PKS2155-304. The plotted count rate is $\approx 90\%$ of the actual one due to the 4 arcminutes extraction radius for the lightcurve data

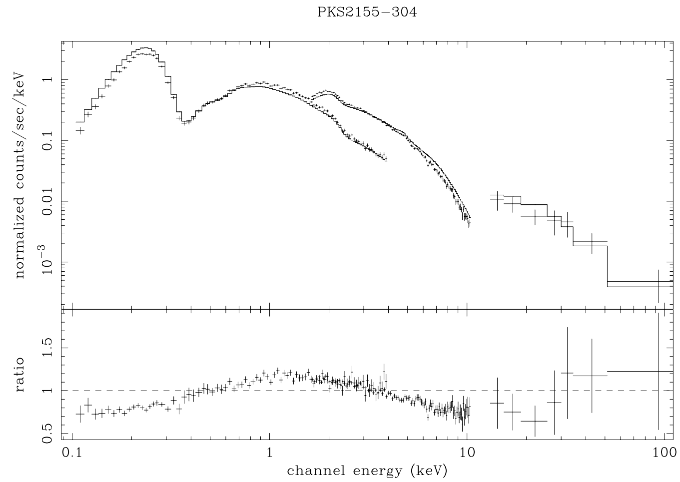


**Fig. 2.** Fit to a power law spectrum. The residuals from the best fit model clearly show spectral curvature up to 10 keV and an excess above 10–20 keV

sure time in this instrument was limited to 36,303 seconds. The data analysis was based on the linearized, cleaned event files obtained from the *BeppoSAX* SDC on-line archive (Giommi & Fiore 1997) and on the XIMAGE package (Giommi et al. 1991) upgraded to support the analysis of *BeppoSAX* data. The average count rate in the MECS was 1.66 cts/s (three units) and 1.59 cts/s in the LECS, after corrections for the instrument PSF and dead time.

The Phoswich Detector System (PDS, Frontera et al. 1997) is made up of four units, and was operated in collimator rocking mode, with a pair of units pointings to the source and the other pair pointing at the background, the two pairs switching on and off source every 96 seconds. The net source spectra have been obtained by subtracting the 'off' from the 'on' counts. The data from the four units have been summed after gain equalization. The Seyfert galaxy NGC7172 is located at about 1.6 degrees from PKS2155-304, but we do not expect any detectable flux contamination in the 1.3 degrees FWHM field of view of the PDS. The High Pressure Gas Scintillation Proportional Counter (HPGSPC, Manzo et al. 1997) observation resulted in an upper limit of $5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ between 10 and 20 keV, which is consistent with the PDS data in the same energy range.

## 3. Time and spectral variability

PKS 2155-304 is well known to be a highly variable source. During the ten EXOSAT observations, which were carried out over a period of two years, PKS 2155-304 changed its flux by about a factor 10 (e.g. Giommi et al. 1990) from $\approx 2. \times 10^{-11}$ to $\approx 2. \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ in the 2–10 keV band. The average flux seen by the *BeppoSAX* imaging instruments of $\approx 6. \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV) is therefore a medium flux level. A detailed timing analysis of the *BeppoSAX* observation of PKS 2155-304 will be presented elsewhere. Here we briefly describe and comment on the main features seen.

A visual inspection of the light curve of PKS 2155-304 (see Fig. 1) shows rapid (timescale of $\approx 10^4$ seconds) and moderate amplitude (up to about 50% peak to peak) intensity variations. Single flares are clearly resolved with rise time approximately equal to decay time suggesting that the geometry within the emitting region is driving the observed light curve.

The PKS 2155-304 spectral slopes seen during EXOSAT and *GINGA* observations (Giommi et al. 1991, Sambruna et al. 1994, Sembay et al. 1993) are a strong function of intensity up to a flux of $\approx 6-8 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ above which the spectral slope does not change much with flux level. Spectral variability was not observed during ROSAT observations when PKS2155-304 was found to be in a very high intensity state (Brinkmann et al. 1994). When X-ray spectral variability is present the spectrum hardens when the source intensity increases, a behaviour that is typical of HBL BL Lacertae objects where the synchrotron break is in the UV/X-ray band (Giommi et al. 1990, Padovani & Giommi 1995). At the medium flux level seen during the *BeppoSAX* observation spectral variations not larger than $\approx 0.1$ in slope are to be expected for the range of variability observed (see Fig. 10 in Sembay et al. 1993). A simple power law fit to the *BeppoSAX* data confirms that the spectral slope changed less than 0.1 from the brightest to the lowest intensity state. In the following we study the 0.1–100 keV spectrum using data from the entire observation.

## 4. Spectral fits

### *4.1. The 1–10 keV continuum*

Spectra were extracted from a 9.0 arcmin radius circular region around PKS2155-304 for the LECS, (which allows the detection of 95% of the photons at 0.28 keV) and from a 4 arcmin region for the MECS which includes about 90% of the flux. Spectral analysis was performed using the XSPEC package and the best instrument calibration available in November 1997. In all cases the $N_H$ has been constrained to be equal or higher than the

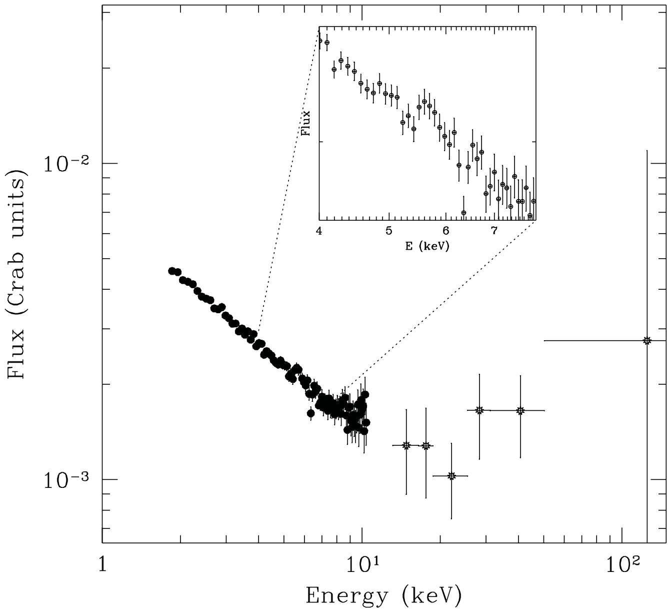


**Fig. 3.** The spectrum of PKS 2155-304 divided by the spectrum of the Crab Nebula. A flux excess at around 5.7 keV (6.4 keV in the rest frame of PKS 2155-304) is apparent

Galactic value along the line of sight of $1.36 \times 10^{20}$ cm$^{-2}$ (measured by F.J Lockman. See Madejski et al. 1997).

Fig. 2 shows the 0.1–100 keV data from the LECS, MECS and PDS instruments together with a fit to a simple power law model. The residuals from the best fit clearly show a curvature between 0.1 and 8–10 keV and an excess above $\approx 20$ keV. The best fit power law energy slope, which is a reasonable representation of the data only in the 1.5–10 keV band, is well within the range observed with EXOSAT (Treves et al. 1989) and close to the one measured with *GINGA* (Sembay et al. 1993) when PKS2155-304 was observed at the same flux level of the *BeppoSAX* observation. The simple power law model over the entire band is clearly unacceptable so we also fitted the data with more complex models. Table 1 summarises the best fit parameters for a power law, a broken power law and a "curved spectrum" defined as

$$F(E) = E^{-(f(E)*\alpha_E + (1-f(E))*\alpha_H)}$$

where $f(E) = (1-exp(-E/E_0))^{\beta}$ and $\alpha_E$ and $\alpha_H$ are the low and high energy asymptotic slopes (G. Matt, private communication). The $\chi^2$values are unacceptably large for the power law and the broken power law model and the improvement obtained using the curved spectrum is highly significant.

More complex fitting involving one or more absorption features have been attempted. The last line in Table 1 shows that the addition of one notch to the "curved" model reduces the $\chi^2$to 188.5 at the expenses of adding three parameters. An F test shows that the $\chi^2$improvement is significant at more than 99% level. We note however, that the magnitude of the feature is very close to the current calibration limit of the LECS instrument and more observations are probably needed to confirm the detection.

### *4.2. The hard tail*

The power law fit to joint LECS, MECS and PDS data (see Fig. 2) shows an excess of radiation above the steep 2–10 keV power law from $\approx 20\ keV$ and up to the highest energy where the source is detected. A different way of showing the presence of the hard component is presented in Fig. 3 where the MECS–PDS spectrum of PKS 2155-304 is divided by the *BeppoSAX* spectrum of the Crab Nebula obtained with the same instruments. This method provides a direct way of visualising the shape of a spectrum and avoids potential problems in the cross-calibration of the instruments since uncertainties apply in equal way to both sources. Since the soft X-ray spectrum of PKS 2155-304 is steeper than that of the Crab Nebula, the data in Fig. 3 follow a steep power law up to about 20 keV followed by a sharp hardening with a slope similar or even flatter than that of the Crab Nebula ($\alpha \simeq 1.$). A fit to the 20–200 PDS points with a power law yields an energy index of $0.7 \pm 0.7$.

### *4.3. A 6.4 keV iron line?*

From Fig. 3 we see that there is indication for an emission feature around 5.7 keV, consistent with a Fe $K_\alpha$ line from cold Fe in the rest frame of PKS 2155-304 (z=0.116 Falomo, Pesce & Treves 1993). We tested the significance of the line detection both on the original data and on the spectral ratio between PKS 2155-304 and Crab. Adding of a Gaussian emission profile to a simple power-law continuum in the 4.–7.5 keV band yields a $\Delta\chi^2 = 11$ for 79 d.o.f. corresponding to an F test significance of $> 99\%$. Rest frame line parameters are $E = 6.40^{+0.12}_{-0.13}\ keV$ and $EW = 40^{+30}_{-20}\ eV$. Although the statistical significance is rather high and no significant calibration problems are known around 5.7 keV, we feel that more systematic analysis of *BeppoSAX* data is necessary for a final confirmation of the $K_\alpha$ line.

## 5. Discussion

The analysis of the average broad-band X-ray spectrum of PKS 2155-304 in a medium intensity state shows a sharp break above 10–20 keV, and a possible detection of a Fe $K_\alpha$ line. Intensity variability is limited to $\approx \pm 25\%$ around a mean value and does not affect the presence of the hard tail. Statistical evidence for a low energy absorption feature was also found close to the calibration limit.

A hard tail above 10 keV was reported in PKS 2155-304 during one HEAO1 observation (Urry & Mushotsky 1982) but *GINGA* observations did not confirm such a finding (Sembay et al. 1993). A spectral hardening in the hard X-ray band is expected from the SSC mechanism and is necessary to explain the gamma ray emission detected by CGRO (Vestrand et al. 1995).

The detection of a Fe $K_\alpha$ line indicates the presence of cold gas, possibly associated with an accretion disk (George & Fabian 1991). Disk emission from PKS 2155-304 might have become detectable in the X-ray band because this part of the spectrum is no longer strongly dominated by the synchrotron

**Table 1.** PKS 2155-304 spectral fits

| model | $N_H^{a}$ | $\alpha_E$ | $\alpha_H$ | $E^{b}_{break}$ | $\beta$ | $E^{b}_{notch}$ | cov. frac. | $\chi^2$ (dof) |
|---|---|---|---|---|---|---|---|---|
| PL | 2.6+/−0.1 | 1.60+/−0.01 | – | – | – | – | – | 774.1 (181) |
| Broken PL | 1.46+/-0.04 | 1.24+/−0.03 | 1.68+/−0.02 | 1.4+/−0.2 | – | – | – | 237.0 (179) |
| Curved | 1.36+0.02 | 1.09+/−0.02 | 1.63+/−0.02 | 2.3+/−0.3 | 0.78 | – | – | 194.0 (178) |
| Curved+ notch | | | | | | 0.55+/−0.04 | $0.05^{+0.06}_{-0.03}$ | 188.5 (175) |

[a] in $10^{20}$ cm$^{-2}$; [b] in keV

component which peaks at UV frequencies (see however the constraints posed by simultaneous optical UV photometry, Urry et al 1993). In this scenario the hard tail could include a component due to Compton reflection from the cold disk.

From the light curve it can be seen that the flares have approximately equal rising and decaying timescales, with no indications of a plateau. It is highly unlikely that the two timescales correspond to the particle acceleration and cooling timescales, since a priori there is no reason for them to be equal. Instead, these timescales may be associated with the dimension of the emitting region, and hence with the light crossing time, provided that both the electron injection and cooling processes operate on time–scales shorter than $R/c$ (where $R$ is the source radius). In this scenario the light crossing time is the only characteristic time that can be observed (Massaro et al. , 1996, Ghisellini et al. 1997). Assuming that the flares are due to quasi–instantaneous injection of electrons and rapid cooling, we require that the synchrotron and self Compton cooling times are equal to or shorter than $R/c$: $t_{cool} = \frac{6\pi mc^2}{\sigma_T c\gamma_o B^2(1+U_S/U_B)} \leq \frac{R}{c}$, where $\sigma_T$ is the Thomson scattering cross section, $\gamma_o m_e c^2$ is the energy of the particles emitting at the observed frequency, $U_B = B^2/(8\pi)$ is the magnetic energy density, and $U_S$ is the radiation energy density of the synchrotron emission (as measured in the comoving frame). The ratio $U_S/U_B$ measures the relative importance of the self–Compton to the synchrotron luminosity, and in PKS 2155–304 it can be estimated by making the ratio of the $\gamma$–ray luminosity (Vestrand et al. 1995) to the optical–UV luminosity, where the synchrotron spectrum peaks. The energy $\gamma_0$ is related to the observed frequency $\nu_o \simeq 3.7 \times 10^6 \gamma_o^2 B\delta/(1+z)$ (assuming synchrotron radiation), and a limit on $R$ is found using $R \sim ct_{var}\delta/(1+z)$, where $\delta$ is the beaming factor. We then obtain the two limits: $B \geq 1.16\,\nu_{17}^{-1/3} t_h^{-2/3}(1+U_S/U_B)^{-2/3}\left(\frac{1+z}{\delta}\right)^{1/3}$, $\gamma_o \leq 1.5\times10^5 \nu_{17}^{2/3}\left[\frac{t_h(1+U_S/U_B)(1+z)}{\delta}\right]^{1/3}$, where $B$ is in Gauss, $t_h$ is the variability timescale measured in hours, and $\nu_o = 10^{17}\nu_{17}$ Hz. Assuming $\delta = 10$, $t_h = 8$, $\nu_{17} = 1$ and $U_S/U_B = 0.5$, we find $B \geq 0.11$ G and $\gamma_o \leq 1.6 \times 10^5$. The upper limit on the energy is particularly important, since it immediately corresponds to an upper limit on the maximum photon energies that can be emitted (by, e.g. the inverse Compton process): $h\nu_{obs} < \gamma_o m_e c^2 \delta/(1+z) = 182\,\delta^{2/3}$ GeV. We then conclude that PKS 2155–304 should not be an important TeV emitter, unlike Mkn 421 and Mkn 501, unless a very high degree of beaming is present.

*Acknowledgements.* We thank G. Fossati and F. Haart for their contribution to the calibration of the low energy response of the LECS instrument. We are also grateful to G. Matt for providing the code used for the "curved spectrum" model.

## References

Boella G. et al. 1997 A&AS, 122, 327
Bregman J. 1994, in Multi-Wavelength Continuum Emission of AGN, T.J.L. Courvoisier and A. Blecha eds., IAU Symp no. 159, p. 5
Brinkmann W. et al. 1994, A&A, 288, 433
Canizares, C.R., Kruper J. 1984 ApJ, 278, L99
Falomo, R., Pesce, J.E., & Treves, A. 1993, APJ 411, L63
Frontera F. et al. 1997 A&AS, 122, 357
Königl A., Kartje J.F., Bowyer S., Kahn, S.M., and Hwang C.Y. 1995, ApJ 446, 598
George, I.M., & Fabian, A.C. 1991, MNRAS, 249, 352
Ghisellini, G., Villata, M., Raiteri, C.M. et al. 1997, submitted to A&A
Giommi P., Barr P., Garilli B., Maccagni D., Pollock A. 1990, ApJ, 356, 455
Giommi, P., Angelini, L., Jacobs, P. &. Tagliaferri G. 1991 in "Astronomical Data Analysis Software and Systems I", D.M.Worrall, C. Biemesderfer and J. Barnes eds, 1991, A.S.P. Conf. Ser. 25, 100
Giommi P., Ansari, S.G., & Micol, A. 1995, A&AS 109, 267
Giommi P.,& Fiore F. 1997, Proc. of "5th International Workshop on Data Analysis in Astronomy, Erice.
Madejski G.M., Mushotzky R.F., Weaver K.A., Arnaud K.A. 1991, ApJ 370, 198
Madejski G.M. et al. 1997 ApJ, submitted.
Manzo G. et al. 1997 A&AS, 122, 341
Massaro, E., Nesci, R. Trevese, D. et al. , 1996, A& A 314, 87
Padovani, P., Giommi, P. 1995 ApJ, 444, 567
Parmar A. et al. 1997 A&AS, 122, 309
Stark A.A., Gammie C.F., Wilson R.W., Bally J., Linke R.A., Heiles C., Hurwitz M. 1992 ApJS, 77
Sambruna R.M., Barr P., Giommi P., Maraschi L., Tagliaferri, A. Treves 1994 ApJ, 434,468
Sembay, S, et al. 1993, ApJ 404,112
Treves A. et al. 1989, ApJ, 341, 733
Urry, C.M., & Moshotsky R.F. 1982, ApJ, 253, 38
Urry, C.M. et al. 1993, ApJ, 411, 614
Vestrand, W.T., Stacy, G., Sreekumar, P. 1995, ApJ 454, L93