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The BL Lacertae objects OQ 530 and S5 0716+714

Simultaneous observations in the X-rays, radio, optical and TeV bands

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Abstract. We present the results of the *Beppo*SAX observations of two BL Lacs, OQ 530 and S5 0716+714, as part of a ToO program for the simultaneous observation at radio, optical, X-ray and TeV energies. Both sources are detected in the LECS and MECS, with S5 0716+714 visible also in the PDS band, up to about ~60 keV. The X-ray spectra of both sources are better fitted by a double power-law model, with a steep soft X-ray component flattening at harder energies, with breaks at 0.3 and 1.5 keV, respectively. The concave shape of the spectra in both objects is consistent with soft X-rays being produced by the synchrotron and harder X-rays by the inverse Compton processes. Also the X-ray variability properties confirm this scenario; in particular, for S5 0716+714 our observation shows variations by about a factor of 3 over one hour below ~3 keV and no variability above. Their simultaneous broad-band energy spectral distributions can be successfully interpreted within the frame of a homogeneous synchrotron and inverse Compton model, including a possible contribution from an external source of seed photons with the different spectral states of S5 0716+714 being reproduced by changing the injected power. The resulting parameters are fully consistent with the two sources being intermediate objects within the "sequence" scenario proposed for blazars.

Key words. BL Lacertae objects: general – X-rays: galaxies – BL Lacertae objects: individual: OQ 530, S5 0716+714

1. Introduction

Blazars are radio-loud active galactic nuclei whose spectra are characterized by variable nonthermal continua emitted by relativistic jets oriented close to the line of sight. They display double peaked spectral energy distributions (SED) extending from radio up to γ-rays and sometimes to TeV frequencies. The first peak (radio to UV/X-rays) is generated by synchrotron emission produced by relativistic electrons flowing along the jet, while the second component (extending to γ-rays) is commonly attributed to inverse Compton emission. The same synchrotron emitting electrons upscatter "seed" photons to higher energies. The origin of this seed radiation field is still debated: it could be the synchrotron radiation itself (SSC models, Maraschi et al. 1992) or produced outside the jets by different mechanisms (ERC, external radiation Compton, see Sikora et al. 1994; Ghisellini & Madau 1996; Dermer & Schlickeiser 1993; Blazejowski et al. 2000). Blazars are divided in two subclasses according to their spectral features: with respect to the presence or the absence of broad emission lines ($EW > 5$ Å) they are classified as flat spectrum radio quasars or as BL Lac objects respectively. BL Lacs are further classified as HBL or LBL according to the position of the synchrotron peak: LBLs peak in optical–UV band while HBLs in X-rays (Padovani & Giommi 1995). The extremely wide energy range of the SED and the high variability of these sources makes simultaneous multiwavelength observations a powerful tool to understand their physics. Therefore we proposed a number of Target of Opportunity *Beppo*SAX observations of blazars in high state of activity, coordinated with optical and TeV monitoring campaigns: the brightening of the source in one of these bands would trigger *Beppo*SAX NFI action. As part of this program we already presented *Beppo*SAX observations of ON 231, PKS 2005–489 (Tagliaferri et al. 2000, 2001) and BL Lac (Ravasio et al. 2002). In this paper

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we report the results of the *Beppo*SAX observations of OQ 530 and S5 0716+714 (the fourth and fifth triggers of our program).

OQ 530 – It was optically identified in 1977 (Kühr 1977) as counterpart of an extragalactic source included in the NRAO-Bonn radio survey at 5 GHz. In 1978, it was classified as a BL Lac by Miller (1978), because of its stellar aspect and the faintness of its optical spectral features. The redshift $z = 0.152$ has been determined from absorption features of the host galaxy as well as from [OII], $\lambda = 3727$ Å and [OIII], $\lambda\lambda = 4959, 5007$ Å emission lines (Stickel et al. 1991; Stickel et al. 1993), confirming previous estimates by Hagen-Thorn & Marchenko (1989). The host galaxy of OQ 530 was studied by Abraham et al. (1991), Stickel et al. (1993), Wurtz et al. (1996) and Scarpa et al. (2000). The data given by these authors, transformed into R_C (Cousins) give slightly different values for the host galaxy magnitude: 16.8, 16.2, 16.6 and 16.1, respectively. The first three used ground based instruments and found the galaxy to be probably an S0, the last ones used HST observations and found the galaxy to be an elliptical, like all other known host galaxies of BL Lac sources. In our monitoring, started in 1994, we never observed OQ 530 fainter than $R_C = 15.8$, so all these values are formally acceptable for the luminosity of the host. Given the systematic uncertainties of these estimates we adopt here an average value of $R_C = 16.5$. The effective radius of the galaxy is found by all authors to be less than 4″, so that it is nearly fully included in our photometric aperture (radius 5″). Our *Beppo*SAX pointing was made when OQ 530 was at $R_C = 14.8$, so the host contribution to the optical flux is not negligible: we estimated this contribution assuming the spectral shape and k-correction for an elliptical galaxy by Fukugita et al. (1995), i.e. $B = 18.59$, $V = 17.17$, $R_C = 16.50$ and $I_C = 15.74$.

In the X-ray band OQ 530 has been detected by the *Einstein* Observatory in May 1980. The data are well fitted by a power law spectrum with $\alpha = 0.48^{+1.0}_{-0.3}$ in the 0.2–3.5 keV range and a flux $F_{1\,\mathrm{keV}} = 0.21$ μJy (Worral & Wilkes 1990). Some years later, in May 1984, a three days EXOSAT observation highlighted a non variable behaviour of the source on short time scales, with a flux of $F_{1\,\mathrm{keV}} \simeq 0.15 \pm 0.02$ μJy (Giommi et al. 1990). ROSAT observed this BL Lac object in July 1990. The 0.1–2.4 keV spectrum is well fitted by a single power law with an energy index $\alpha = 1.04 \pm 0.05$ and flux $F_{1\,\mathrm{keV}} = 0.32$ μJy (Comastri et al. 1995). *Beppo*SAX already observed OQ 530 in February 1999. The source was detected by the LECS and MECS (<10 keV) but not by the PDS. A single power law model fit the data ($\alpha = 0.55^{+0.27}_{-0.32}$), but the residuals towards low energies suggest a concave spectrum (Giommi et al. 2002).

The optical light curve of OQ 530 from 1905 until 1977 was derived by Miller (1978) using the Harvard College plate collection. A further study from 1966 to 1980 was performed by Barbieri et al. (1982) using the Asiago Schmidt plates. A reanalysis of these works, and an updating of the light-curve until 1997 was made by Nesci et al. (1997). A collection of published data until 1993 has been recently published by Fan & Lin (2000). The source shows an average monotonic decreasing trend since the beginning of 1900, when it was at $B \sim 12$, until 1995 when its average value was $B \sim 16$, with fast and irregular variations of about 1.5–2 mag. It is still monitored by some of us (Perugia and Roma groups). On the night of February 14, 2000, we found the source very bright in the optical with $R_C = 14.3$. Thus, we triggered the *Beppo*SAX ToO, but due to constraints on the satellite pointing, the source was observed only on March 3, 2000, when it had a magnitude of $R_C = 14.9$. Moreover, due to problems with the satellite, the observation lasted less than 27 ks, instead of the 50 ks allocated. A second pointing was then performed on March 26, for about another 23 ks; during this second pointing the R_C magnitude was 14.8. In both cases the source was weak in the X-rays and detected only up to 10 keV (see Sect. 2).

S5 0716+714 – It was discovered in 1979 as the optical counterpart of an extragalactic radio source during another Bonn-NRAO survey (Kühr et al. 1981). Two years later it was classified as a BL Lac by Biermann et al. (1981) because of its featureless optical spectrum and high linear polarisation. It is one of the brightest and most variable BL Lac objects, but, despite the many attempts to measure its redshift (the last one by Rector & Stoke 2001, with the Keck telescope), only a lower limit $z > 0.3$ has been estimated by Schalinski et al. (1992) and Wagner et al. (1996) on the basis of the non detection of a host galaxy in deep images.

S5 0716+714 was first detected in the X-ray band by the *Einstein* Observatory, but the flux was too low for a detailed spectral analysis (Biermann et al. 1981). In 1991 March 8–11, the source was observed several times with the ROSAT PSPC detector (0.1–2.4 keV) (Cappi et al. 1994; Urry et al. 1996; Wagner et al. 1996) and was found to be bright and rapidly variable with a mean flux of $\sim 10^{-11}$ erg cm^{-2} s^{-1}. S5 0716+714 has been already observed twice by *Beppo*SAX, in 1996 November 14 and in 1998 November 7 (Giommi et al. 1999) but the source was not very bright and it was detected only up to 10 keV. The *Beppo*SAX SEDs showed the presence of a steep power law component below ~2.5 keV with a spectral index $\alpha_1 \sim 1.5$ becoming harder towards higher frequencies, with an index $\alpha_2 \sim 0.85$. The former component was also found to be variable in correlation with the optical flux on a time scale of a few hours (Giommi et al. 1999).

S5 0716+714 has been regularly monitored in the optical since the end of 1994; a very bright level was recorded in February 1995 (Ghisellini et al. 1997), when it reached the magnitude of 12.78 in the R_C bandpass, while in the following two years it has never been observed brighter than $R_C = 13.0$. A new strong outburst occurred in September 1997 when S5 0716+714 was even brighter than in 1995 at $R_C = 12.58$ (Massaro et al. 1999). After a relatively quiet period, in October 2000 we measured an optical flux comparable to that of September 1997 and a *Beppo*SAX ToO was activated. Unfortunately, for technical reasons the pointing was performed a week after the occurrence of the optical maximum and the brightness of S5 0716+714 had already decreased by about half a magnitude. In any case, it was brighter than in the two previous *Beppo*SAX observations, when it was around $R_C = 13.8$, and, for the first time, it was detected in the hard X-rays by the PDS up to about 60 keV.

The paper is organised as follows: in Sect. 2 we present the *Beppo*SAX observations and data analysis and in Sect. 3 the radio, optical and TeV observations; in Sect. 4 we present the SEDs of the two sources in the framework of an SSC model. The discussion is given in Sect. 5.

2. *Beppo*SAX observations and data reduction

*Beppo*SAX observed OQ 530 (1418+546) twice during 2000 (March 3–4, March 26–27). In both observations the source was not detected by the PDS.

S5 0716+514 was observed for about one day from October 30 to October 31, 2000; and it was detected up to ~60 keV.

Standard procedures and selection criteria were applied to the data to avoid the South Atlantic Anomaly, solar, bright Earth and particle contamination using the SAXDAS v. 2.0.0 package. Exposures and count rates of the observations are reported in Table 1.

Data analysis was performed using the software available in the HEAsoft Package (XIMAGE 3.01, XSELECT v2.0, XSPEC 11.0.1, XRONOS 5.16). LECS and MECS images displayed a bright pointlike source: events for spectral and timing analysis were extracted from circular regions centered on the source, with radii of 8 and 4 arcmin, respectively. We extracted LECS and MECS background events in the same way, from off source regions of the field of view and checked the constance of the count rates during the whole observation. In any case, since LECS and MECS backgrounds are not uniformly distributed across the detectors, we choose to use background files extracted from long blank field exposures, available from the SDC public ftp site (Fiore et al. 1999). The spectral analysis were performed with the XSPEC 11.0.1 package, using the updated (01/2000) response matrices.

The PDS was operated in the customary collimator rocking mode, where half the collimator points at the source and half at the background and they are switched every 96 s. The background-subtracted PDS spectrum for S5 0716+714 was obtained from the standard pipeline analysis carried out at the *Beppo*SAX Science Data Center.

2.1. OQ 530

Because of the faintness of the source and the short duration of the runs the source was not detected by the PDS, as can be seen from Table 1, and the 3σ upper limit does not add any useful information to the X-ray spectrum (e.g. for the SED in Fig. 6 below). From the comparison of LECS and MECS data with background files we decided to constrain further the energy range of our analysis to 0.13–8.7 and 0.13–10 keV for the 3–4 and 26–27 of March observations, respectively.

For both observations we have poor statistics at low energies (LECS band) and it is difficult to obtain a reliable fit to the observed spectrum. We rebinned the LECS energy channels in order to have more than 25 net counts in each bin: this is a good compromise between having a sufficient number of bins and significant number of counts in each of them. The MECS detected a slightly higher number of events, so we rebinned them to have 30 net counts in each bin.

We fitted our spectra adopting the galactic interstellar absorption $N_{\rm H} = 1.18 \times 10^{20}$ cm^{-2}, as measured by Dickey & Lockman (1990). Fitting the 3–4 March spectrum with a single power law model leaves large residuals at low energies and the quality of this fit is evidently poor ($\chi^2_r/d.o.f. = 1.64/23$). Therefore we tried to fit the spectrum with the sum of two power law models and we obtained a very steep soft X-ray spectral index $\alpha_1 = 6.7^{+0.2}_{-1.8}$ and a flatter one towards higher energies $\alpha_2 = 0.40 \pm 0.2$ (throughout the paper the errors are at 90% confidence interval for one parameter of interest, i.e. $\Delta\chi^2 = 2.7$). The two power laws cross at $E_b \sim 0.3$ keV. This model gives a better fit ($\chi^2_r/d.o.f. = 0.96/21$, F-test probability >99.9%), but because the break is near to the soft limit of our energy range and we have only a few counts in this part of the spectrum, we can not really constrain the soft component of the two power law model. This soft X-ray excess is probably due to the very steep tail of the synchrotron component. At energy higher than ~0.5 keV, instead, we are probably observing an inverse Compton component.

We repeated the procedure for the observation of 26–27 March. A single power law fits the data better than in the first observation, however towards low energies hints of positive residuals are still evident. We obtain $\alpha = 0.75 \pm 0.20$ ($\chi^2_r/d.o.f. = 1.03/21$). The measured fluxes between the two observations are quite similar, $F_{2-10\,{\rm keV}} \sim 10^{-12}$ erg cm^{-2} s^{-1} (Table 2). We performed the fit also with the sum of two power laws. As in the previous observation, in the soft X-ray band we find a very steep component, with practically the same spectral index $\alpha_1 = 6.7$, but with even larger uncertainties (basically we can not constrain this component). At higher energies the second spectral index is $\alpha_2 = 0.65 \pm 0.2$. With this model we obtain a lower χ^2_r ($\chi^2_r = 0.95$), but an F-test reveals that the improvement of the fit in this case is only marginally significant (~80%). In Table 2 we report a summary of our analysis.

Also during the 1999 *Beppo*SAX observation, Giommi et al. (2002) have an indication of a better fit with a broken power law ($\alpha_1 = 1.3$, $\alpha_2 = 0.4$, and $E_b = 1.8$ keV). However, their statistics is even lower and the fit improvement is marginally significant. In Table 3 we report all the published spectral parameters for the OQ 530 X-ray observations. The spectral shape of the source seems to be almost constant, except for the ROSAT observation, that found a steeper spectrum. This is probably due to a mixture of the soft and hard components, that the PSPC was not able to disentangle. The 1 keV flux density is quite variable; the faintest measured 1 keV flux (by *Beppo*SAX, in 1999) is in fact more than three times weaker than the highest one (ROSAT 1990).

We performed the temporal analysis of our observations in the two bands 0.2–1.8 keV LECS and 1.8–6 keV MECS. Because of the faintness of the source we choose a time binning of 1 hour, in order to reduce uncertainties caused by the poor statistics. During both observations we did not detect variability.

2.2. S5 0716+714

During the *Beppo*SAX observation of October 2000, S5 0716+514 was detected also by the PDS, so we could perform our analysis on a wider energy range (0.15–57 keV).

Table 1. Journal of *Beppo*SAX observations. [a] 0.1–10 keV; [b] 1.5–10 keV; [c] 12–100 keV. For OQ 530 the PDS count rates are lower than the uncertainties and we excluded these data from our analysis.

	OQ 530					
	LECS		MECS		PDS	
Date	exposure (s)	count rate[a]	exposure (s)	count rate[b]	exposure (s)	count rate[c]
3–4 March 2000	19 625	$(7.4 \pm 0.8) \times 10^{-3}$	26 633	$(1.3 \pm 0.1) \times 10^{-2}$	10 270	$(1 \pm 6) \times 10^{-2}$
26–27 March 2000	17 181	$(8.2 \pm 0.9) \times 10^{-3}$	22 718	$(1.1 \pm 0.1) \times 10^{-2}$	10 361	$(2 \pm 6) \times 10^{-2}$
			S5 0716+714			
30–31 October 2000	19 192	$(4.7 \pm 0.2) \times 10^{-2}$	43 459	$(5.6 \pm 0.1) \times 10^{-2}$	22 444	(0.12 ± 0.04)

Table 2. X-ray spectral parameters and fluxes. * cts keV^{-1} cm^{-2} s^{-1}. ** erg cm^{-2} s^{-1}. The values are obtained performing the fit with the absorption parameter fixed at the galactic value $N_{\rm H} = 1.18 \times 10^{20}$ cm^{-2} for OQ 530 and $N_{\rm H} = 3.9 \times 20^{20}$ cm^{-2} for S5 0716+714 (Dickey & Lockman 1990). ^{a} fit performed only on the LECS+MECS data, ^{b} added also the PDS data to the fit. The reported uncertainties are the 90% confidence ranges for one parameter of interest, i.e. $\Delta\chi^2 = 2.7$.

			OQ 530					
Date	α_1	K_1^* ($\times 10^{-4}$)	α_2	K_2^* ($\times 10^{-4}$)	$F_{1\,\rm keV}$ μJy (1)	(2)	$F^{**}_{2-10\,\rm keV}$ ($\times 10^{-12}$)	$\chi^2_r/d.o.f.$
3–4 March	0.55 ± 0.2	$2.1^{+0.6}_{-0.5}$			0.14		1.1	1.64/23
3–4 March	$6.7^{+0.2}_{-1.8}$	$\sim 10^{-3}$	0.40 ± 0.2	1.8 ± 0.5	$\sim 10^{-4}$	0.12	1.2	0.96/21
26–27 March	0.75 ± 0.20	$2.5^{+0.5}_{-0.6}$			0.16		0.9	1.03/21
26–27 March	6.7±?	$\sim 10^{-3}$	0.65 ± 0.2	2.25 ± 0.55	$\sim 10^{-4}$	0.15	1.0	0.95/19
			S5 0716+714					
30–31 October, 2000^a	1.25 ± 0.08	16.4 ± 1.2			1.1		2.9	1.99/76
30–31 October, 2000^b	$2.40^{+0.4}_{-0.3}$	10.2 ± 0.45	$0.60^{+0.25}_{-0.35}$	$6.2^{+3.3}_{-3.0}$	0.7	0.4	3.3	0.92/77

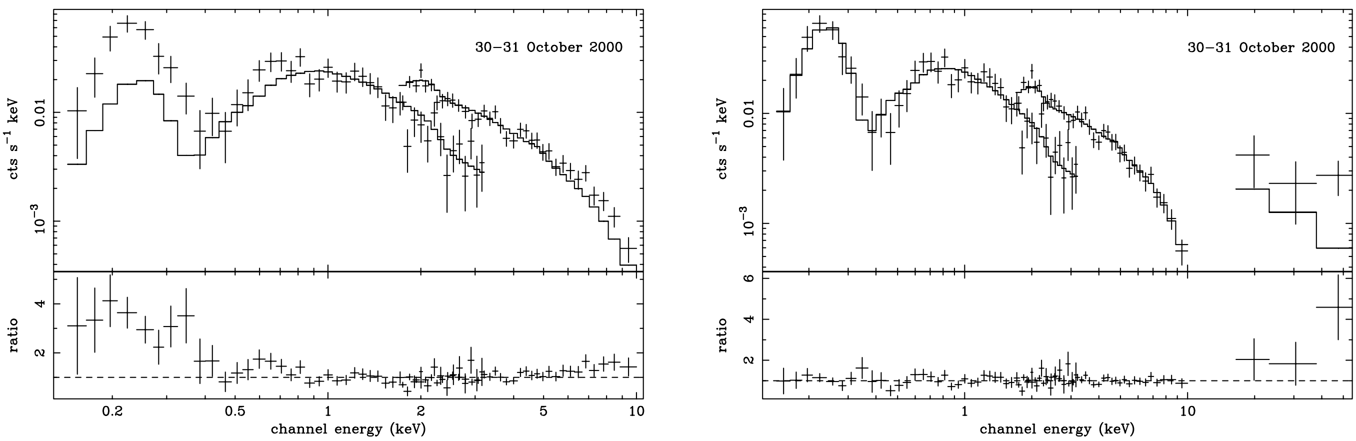

Fig. 1. Left panel: LECS+MECS S5 0716+714 spectrum fitted by a single power law model. Positive residuals are evident below ∼1 keV; they get larger towards lower energies. Right panel: LECS+MECS+PDS S5 0716+714 spectrum fitted by a two power law model. In both cases we fitted the data with the absorption parameter fixed at the galactic value $N_{\rm H} = 3.9 \times 10^{20}$ cm^{-2} (Dickey & Lockman 1990).

We performed a preliminary analysis on LECS+MECS and MECS+PDS data alone, in order to get some useful hints for fitting the whole spectrum. Initially we fitted the spectra with single power laws, keeping the absorption parameter fixed at the galactic value: $N_{\rm H} = 3.9 \times 10^{20}$ cm^{-2} (Dickey & Lockman 1990). The LECS+MECS spectrum is badly fitted by this model ($\chi^2_r/d.o.f. = 1.99/76$), with large positive residuals below 0.5 keV (see Fig. 1). Therefore we fitted it again with a two power law model. This model fits the data much better ($\alpha_1 = 2.5$ $\alpha_2 = 0.7$, $\chi^2_r/d.o.f. = 0.86/74$). The two power laws cross at ∼1 keV. The MECS+PDS spectrum is instead fitted quite well by a single power law model, with a spectral index somewhat steeper than the second spectral index of the LECS+MECS two power law fit ($\alpha = 0.9$, $\chi^2_r/d.o.f. = 1.08/36$). However, we note that due to the weak signal in the PDS, the fit is clearly dominated by the MECS data. A detailed analysis of the PDS light curve in search for spikes gave negative results. This, together with the lack of

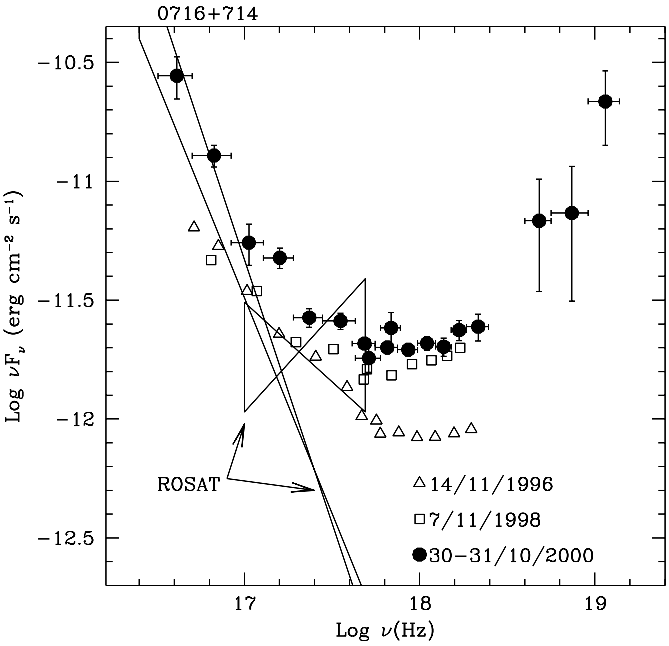

Fig. 2. X-ray spectral energy distribution of S5 0716+714 during the October 2000 *Beppo*SAX observation (filled circles). We plotted also November 1996 (open triangles), November 1998 (open squares) *Beppo*SAX (Giommi et al. 1999) and 1991 ROSAT SEDs (Cappi et al. 1994).

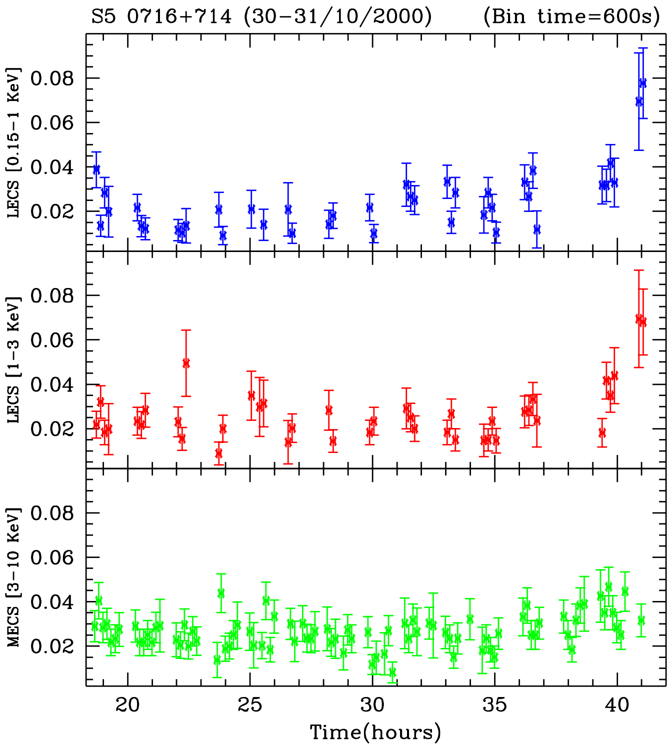

Fig. 3. LECS 0.15–1 keV (top panel), 1–3 keV (mid panel) and MECS 3–10 keV (bottom panel) light curves of S5 0716+714 during the *Beppo*SAX observation of October 2000. The time bin is of 10 min. Bins with less than 20% effective exposure time have been excluded. Time axis is hours starting from October 30, 2002.

other obvious X-ray sources inside our field of view, confirm us on the reality of the PDS detection. We then fitted the whole LECS+MECS+PDS spectrum with a two power law model, finding a good fit to the data ($\chi^2_r/d.o.f. = 0.92/77$). The two power laws cross at ~1.5 keV. In Table 2 we report the best-fit parameters.

Although S5 0716+714 was not at its maximum recorded optical luminosity ($R_C \simeq 12.5$), measured a few days before our X-ray observation, it was still about 0.8 mag brighter than during the two previous *Beppo*SAX exposures (Giommi et al. 1999). It was brighter than the previous observations also in the X-ray band (Table 3). During our observation the source was in an X-ray state higher in flux but similar in shape to that detected by ROSAT in 1991, when it was revealing again a concave spectrum with an energy break at ~0.8 keV (Cappi et al. 1994; Comastri et al. 1995). The historical SED in the X-ray band is displayed in Fig. 2. In all observations the transition between the steep soft X-ray component and the much harder spectrum at higher X-ray energies is clearly detected. During our observation the soft X-ray spectrum is steeper ($\alpha_1 = 2.4$), than during the previous *Beppo*SAX observations ($\alpha = 1.7$ in 1996; $\alpha = 1.3$ in 1998). This seems to confirm the trend noticed by Giommi et al. (1999) of a steeper soft X-ray spectrum when the source is brighter.

We performed the temporal analysis of our observation in the three different energy bands: 0.15–1.0, 1.0–3.0 and 3.0–10 keV. In Fig. 3 we display the two LECS and the higher energy MECS light curves. They seem almost constant for the first 20 hours of the observation. Then the two LECS fluxes increase by a factor of three on a time scale of one hour. This variation could be even larger since our measurements stopped before detecting any fading. The source displayed a similar behaviour also in the 1.5–3.0 keV MECS band (not plotted here). In spite of the formal break that seems to be at around 1.5 keV, the emission in the two softer energy bands are clearly connected. Clearly, the soft X-ray component component is still relevant in the 1–3 keV band. However, by selecting only the counts above 2 keV we find that the variability is much less pronounced. The variability is essentially absent in the 3–10 keV band, where the hard X-ray component is dominant (Fig. 3). A similar behavior was already detected in a previous *Beppo*SAX observation (Giommi et al. 1999).

3. Optical, radio and TeV data

3.1. OQ 530

The optical R_C light curve since February 1996 of the source is shown in Fig. 4. It is characterized by a large variability with fast and strong flares (of the order of half magnitude in a few days). The average trend seems to be decreasing until the beginning of 1999, when an increasing trend seems to begin. The average value was $R_C = 15.3$ in the period Jan. 1997–Aug. 1999 (JD 400–1400) so that our observation at $R_C = 14.3$ on Feb. 14, 2000 was clearly indicative of a remarkably bright state. During the first *Beppo*SAX pointing on March 3 the source had already dropped at $R_C = 14.9$ and remained stable within 0.03 mag; during the second one (March 26) the source was about at the same optical luminosity but we could observe it only for

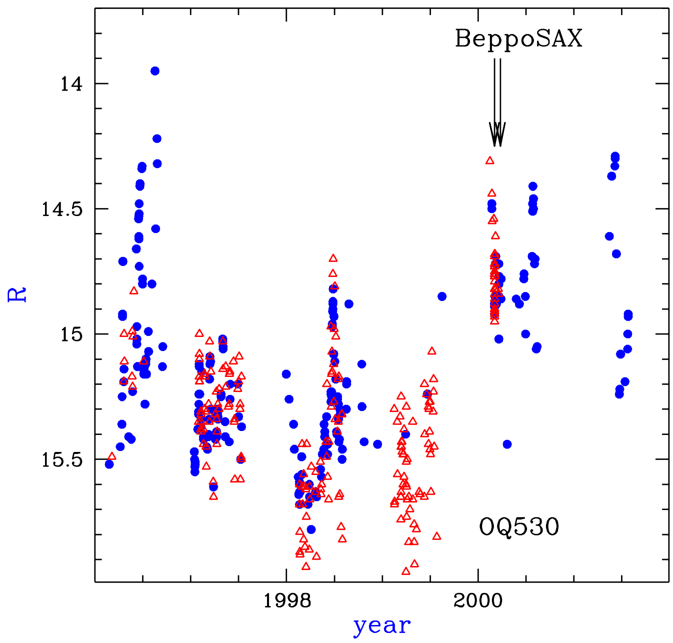

Fig. 4. The optical, R_C magnitude, light curve of OQ 530 since February 1996. Open triangles are data from the Perugia observations (the typical error for these measurements is of the order of 0.1 mag), filled circles are from Roma (the typical error for these measurements is of the order of 0.01–0.02 mag). The two arrows indicate the dates of the *Beppo*SAX pointings, activated by a flare-like episode, but carried out when the source had already faded to $R_C \sim 15$ mag (see text).

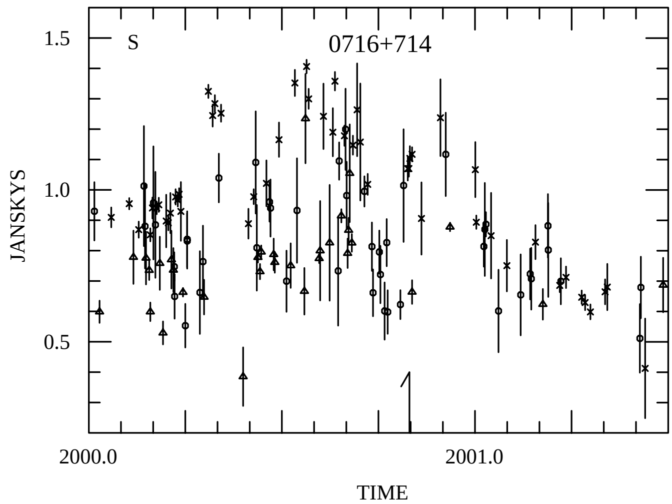

Fig. 5. The 1.5 years light curve of S5 0716+714 at three radio frequencies: triangles are data at 4.8 GHz, open circles data at 8.0 GHz, and × denotes data at 14.5 GHz. The measurements are given as daily averages. The source show erratic variability during all year 2000, then there seem to be a steady decline in the fluxes.

a short time due to bad weather conditions. Between the two *Beppo*SAX pointings the source remained substantially constant, with small (~0.1 mag) variations. The energy spectral slope ($F_\nu \propto \nu^{-\alpha}$) from our *BVRI* observations was 1.63 ± 0.06, a typical value for the source at this luminosity level (D'Amicis et al. 2002). On the other hand, the spectral shape (and flux levels) is affected by the contribution of the host galaxy, and in Fig. 6 the simultaneous optical points have been galaxy-subtracted, using the host magnitude given in the Introduction.

Very long baseline interferometric radio observations with EVN at 5 GHz were performed one year before (February 1999) and one year after (June 5, 2001) the *Beppo*SAX pointing by some of us (Massaro et al. 2002). The source showed a core-jet structure, already detected in 1996 (Fomalont et al. 2000): the core had a flux density of 440 mJy at that epoch, but dropped to 204 mJy on February 1999 and rose again up to 685 mJy on June 2001. This increase, larger than a factor of 3, of the core radio brightness supports the development of strong activity following the optical burst of February 2000.

OQ 530 has been pointed in the TeV band by the HEGRA telescopes from July 1 to July 16 1999, and on March 5 2000. The total exposure time is of 9.7 hours, a quarter of which is from the March observation (1 day after the *Beppo*SAX observation). The source was never detected with a total upper limit $UL(99\%, E > 1.1 \text{ TeV}) = 1.35 \times 10^{-12}$ photons cm^{-2} s^{-1} (Aharonian et al., HEGRA collaboration, 2002, in preparation).

3.2. S5 0716+714

As stated in the Introduction, the source was very bright the week before the *Beppo*SAX observation: $R_C = 12.55 \pm 0.02$ mag on October 22 and 12.58 ± 0.03 on October 28. Only few optical photometric data, taken during the X-ray pointing, are available, but these are enough to derive the SED and to compare it with that of previous observations. In particular, R_C and I_C were measured equal to 13.05 ± 0.04 and 12.55 ± 0.04 mag at 22:40 UT (October 30) with the 0.5m reflector of the Astronomical Station of Vallinfreda (Rome). On November 1 22:10 UT its luminosity has faded at $R_C = 13.31$ (Vallinfreda), indicating that over the entire period S5 0716+714 showed brightness variations on intraday time scale with amplitude of a few tenths of magnitude, as is usually observed in this source (Nesci et al. 2002).

During the *Beppo*SAX observation the radio flux of S5 0716+714 was monitored at the UMRAO, using the procedures and calibrators described in Aller et al. (1985). At 14.5 GHz, from October 28 to November 1, the flux density remained constant with a mean value of 1.1 Jy. Other measurements at 8.0 GHz, performed from October 1 to 21 give a flux density in the range 0.60–0.85 ± 0.1 Jy. In Fig. 5 we plot the 1.5 years radio light curve of S5 0716+714 at three frequencies. The source seems to be in an active state up to the end of year 2000, then there seems to be a steady decline in the fluxes.

During our *Beppo*SAX observation S5 0716+714 has been observed also in the TeV band by the HEGRA telescopes for about 2 hours on October 31 2000. However, the source has not been detected with an upper limit $UL(99\%, E > 1.7 \text{ TeV}) = 2.5 \times 10^{-12}$ photons cm^{-2} s^{-1} (Aharonian et al., HEGRA collaboration, 2002, in preparation).

Table 3. OQ 530 and S5 0716+714 X-ray spectral parameters. (1) Worrall & Wilkes (1990); (2) Comastri et al. 1995; (3) Padovani et al., in prep.; (4) Cappi et al. (1994); (5) Giommi et al. (1999).

Date	Mission	α_1	α_2	$F_{1\,\mathrm{keV}}$ μJy	$F_{2-10\,\mathrm{keV}}$ $\times10^{-12}$ erg cm^{-2} s^{-1}	Ref.
OQ 530						
December 1980	Einstein	$0.48^{+1.0}_{-0.3}$		0.21		1
July 1990	ROSAT	1.04 ± 0.05		0.32		2
February 1999	*Beppo*SAX	$0.55^{+0.27}_{-0.32}$		0.09	0.67	3
3–4 March 2000	*Beppo*SAX	0.55 ± 0.2		0.14	1.1	
26–27 March 2000	*Beppo*SAX	0.75 ± 0.2		0.16	0.9	
S5 0716+714						
8 March 1991	ROSAT	2.67 ± 0.12	1.00	0.78		4
14 November 1996	*Beppo*SAX	1.7 ± 0.3	0.96 ± 0.15	0.13	1.4	5
7 November 1998	*Beppo*SAX	1.3 ± 0.4	0.73 ± 0.18	0.19	2.6	5
30–31 October 2000	*Beppo*SAX	$2.40^{+0.4}_{-0.3}$	$0.60^{+0.25}_{-0.35}$	1.1	3.3	

4. The spectral energy distributions

We have used a homogeneous, one-zone synchrotron inverse Compton model to reproduce the SEDs of our sources. The model is very similar to the one described in detail in Spada et al. (2001), it is the "one-zone" version of it. Further details can be found in Ghisellini et al. (2002), where the same model has been applied to less powerful BL Lacs. The main assumptions of the model are:

– the source is cylindrical, of radius R and thickness $\Delta R' = R/\Gamma$ (in the comoving frame, where Γ is the bulk Lorentz factor);
– the source is assumed to emit an intrinsic luminosity L' and to be observed at a viewing angle θ with respect to the jet axis;
– the particle distribution $N(\gamma)$ is assumed to have the slope n [$N(\gamma) \propto \gamma^{-n}$] above the random Lorentz factor γ_c, for which the radiative (synchrotron and inverse Compton) cooling time equals $\Delta R'/c$. The motivation behind this choice is the assumption that relativistic particles are injected in the emitting volume for a finite time, which we take roughly equal to the light crossing time of the shell. This crossing time is roughly equal to the time needed for two shells to cross, if they have bulk Lorentz factor differing by a factor around two. The electron distribution is assumed to cutoff abruptly at $\gamma_{\rm max} > \gamma_c$. We then assume that between some $\gamma_{\rm min}$ and γ_c the particle distribution $N(\gamma) \propto \gamma^{-(n-1)}$. This choice corresponds to the case in which the injected particle distribution is a power law ($\propto \gamma^{-(n-1)}$) between $\gamma_{\rm min}$ and $\gamma_{\rm max}$, with $\gamma_{\rm min} < \gamma_c$. Below $\gamma_{\rm min}$ we assume $N(\gamma) \propto \gamma^{-1}$. The value of $\gamma_{\rm max}$ is not crucial, due to the fact that the electron distribution, for our sources, is steep. It has been chosen to be a factor ~100 larger than $\gamma_{\rm min}$.

The simultaneous optical observations help in defining the low frequency peak of the SED, which in both sources must be located at frequencies lower than the optical. This helps to constrain the values of the input parameters of our model. Since we determine $\gamma_{\rm peak}$ as the energy of those electrons that can cool in the injection time (i.e. $\gamma_{\rm peak} = \gamma_c$), there is a relation between $\nu_{\rm peak}$ and the cooling rate. If the latter is dominated by synchrotron emission, the location of $\nu_{\rm peak}$ constrains the value of the magnetic field. This in turn fixes the amount of inverse Compton radiation. According to our simultaneous data, the slope of the optical emission for both sources is steep (i.e. $\alpha > 1$), requiring the synchrotron part of the spectrum to peak below the optical band. On the other hand, the infrared data, even if not simultaneous, suggest that $\nu_{\rm peak}$ cannot be far below the optical. This motivates the choice of the adopted $\nu_{\rm peak}$ as listed in Table 4.

The remaining degree of freedom for the choice of the input parameters is due to the value of the beaming factor (i.e. Γ and the viewing angle θ), and to the redshift. Another important input parameter is the size of the emitting region. The extremely rapid variability shown by S5 0716+715 during our observations refers to the soft X-ray flux, while timescales of the order of a ~day are typical in the optical (see e.g. Ghisellini et al. 1999), at frequencies closer to the synchrotron peak. The size of the emitting region is therefore constrained to be less than one light-hour or a light-day (i.e. $R \le ct_{\rm var}\delta/(1+z)$). Although a one-zone homogeneous model is forced to use the minimum variability timescale observed at any band to constrain the size, it is also clear that this model is a simplification of a scenario which may be more complex. Our choice of $R = 2 \times 10^{16}$ and $\delta \sim 17$ corresponds to a minimum variability timescale of $t_{\rm var} \sim 11(1+z)$ hours. Assuming a more compact homogeneous source, while more in agreement with the soft-ray variability, implies a more dominant self Compton component, unless a larger beaming factor is also assumed. For the redshift, since only the lower limit $z = 0.3$ is known for S5 0716+714, we have assumed $z = 0.3$ in all our calculations for S5 0716+714 but one case, for which $z = 1$ has been assumed, in order to check what are the output parameters mostly affected by the choice of a particular redshift.

We have tried to reproduce the three SEDs of S5 0716+714 by changing the minimum possible number of input

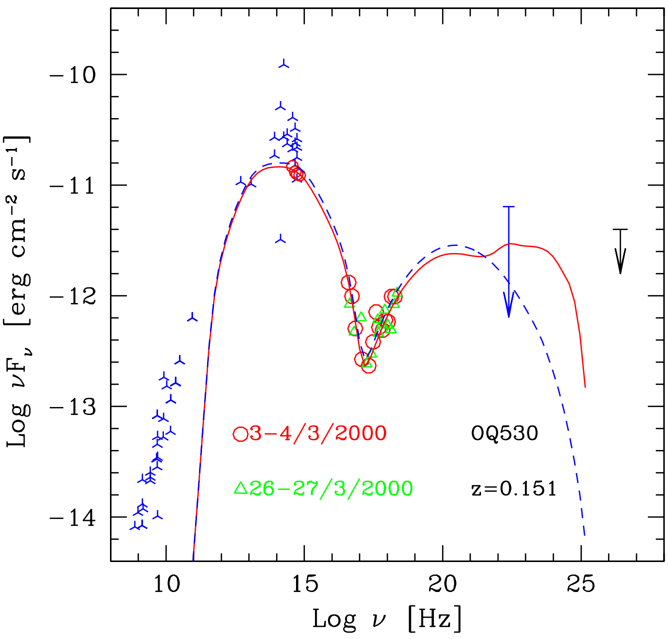

Fig. 6. The SED of OQ 530. Star symbols are from the NASA Extragalactic Database (NED). The solid line refers to the SSC plus EC model, while the dashed line corresponds to a pure SSC model, with no contributions from seed photons generated externally to the jet. All other parameters of the two models are the same.

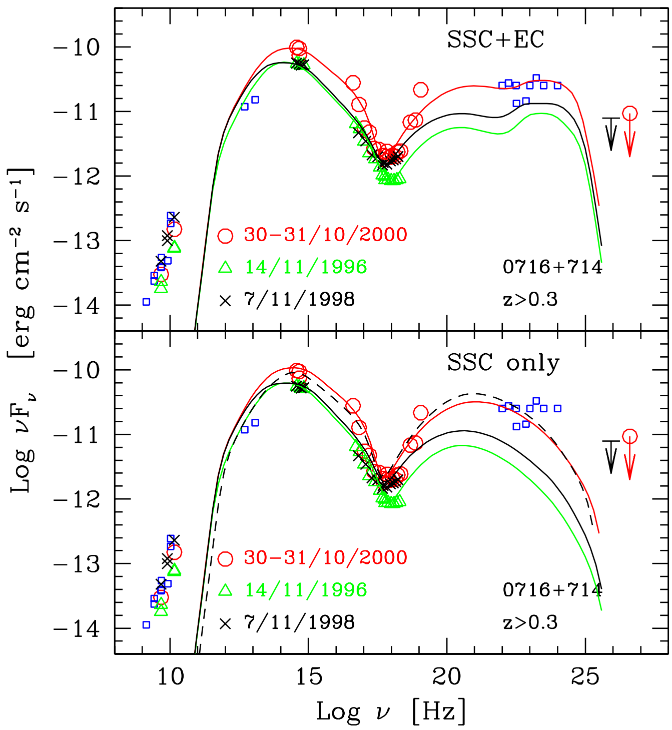

Fig. 7. The SED of S5 0716+714. In the top panel we show as solid lines the SSC plus external Compton model we have applied to the three labeled observing campaigns. For all models $z = 0.3$ was assumed. The bottom panel shows pure SSC models, with no contributions from seed photons generated externally to the jet. The other input parameters are the same (solid lines), while $z = 1$ is assumed for the dashed line. The square symbols refer to not simultaneous observations taken from NED and from Lin et al. (1995).

parameters: the most significant change is in the injected luminosity, which in Oct. 2000 is found to be twice as much as in 1996 and 1998.

An important consequence for our modeling is that the SSC component alone cannot reproduce the observed emission in the EGRET band in S5 0716+714, as shown in the bottom panel of Fig. 7. Since these γ-ray data are not simultaneous, there is in principle no need to reproduce them. However, since the source should be in a bright state, it may be likely that the level of γ-ray emission during our campaign was similar to what EGRET previously found (Lin et al. 1995). If we want to account for a flux in the 0.1–10 GeV band similar to what found by EGRET, we should then consider the possibility that the high energy emission can be produced by the scattering of external soft photons, either produced in a putative broad line region or in the accretion flow. We have allowed for some external Compton radiation by assuming the presence of external photons produced by, e.g. a broad line region of relatively low luminosity, as listed in Table 4. The effect of this mechanism is to produce the second "hump" at the largest γ-ray energies, as shown by the solid line in Fig. 6 (for OQ 530) and by the top panel of Fig. 7 (for S5 0716+714). This high energy bump is due to the fact that the seed photons due to the emission lines, in the comoving frame, are at the typical frequency of $10^{15}\Gamma$ Hz, larger than the synchrotron peak frequency in the same frame, which is $\nu_{\rm peak}/\delta \sim \nu_{\rm peak}/\Gamma$).

The possibility of a broad line region in objects such as S5 0716+714 is questionable: the line emission could be variable (as in BL Lac itself), or always very weak (as seems to be the case for low power, high frequency peaked BL Lacs). On the other hand, to produce extra inverse Compton emission, other processes could be important, as in the "mirror model" discussed by Ghisellini & Madau (1996). Therefore the values listed in Table 4, which formally refer to the broad line region, could instead be appropriate for other possible contributors of seed photons. Note that for OQ 530 there are only upper limits for the γ-ray flux, which are not stringent enough to constrain the presence of any external component (compare the solid and dashed lines).

The input parameters are listed in Table 4 and the models are shown in Figs. 6 and 7. The applied model is aimed at reproducing the spectrum originating in a limited part of the jet, thought to be responsible for most of the emission. This region is necessarily compact, since it must account for the fast variability shown by all blazars, especially at high frequencies. The radio emission from this compact region is strongly self-absorbed, and thus the model cannot account for the observed radio flux. This explains why the radio data are systematically above the model fits in the figures.

5. Discussion

We presented the results of *Beppo*SAX ToO observations of two BL Lac objects observed while they were in a high state. Once again these observations were triggered from optical monitoring. In our ToO program we have probably been biased toward sources that have an higher optical variability.

Table 4. Model input parameters. Column (1): name of the source; Col. (2): observation date; Col. (3): intrinsic luminosity L'; Col. (4): luminosity of broad emission lines $L_{\rm BLR}$: the first value (i.e. zero) corresponds to assume no contribution of external photons to the formation of the IC spectrum; Col. (5): dimension of the broad line region $R_{\rm BLR}$; Col. (6): magnetic field B; Col. (7): size of the emitting region R; Col. (8): bulk Lorentz factor Γ; Col. (9): viewing angle θ (in degrees); Col. (10): beaming factor δ; Col. (11): slope of the particle distribution n; Col. (12): minimum Lorentz factor of the injected electrons $\gamma_{\rm min}$; Col. (13): Lorentz factor of the electron emitting at the peaks, $\gamma_{\rm peak}$; Col. (14): synchrotron peak frequency $\nu_{\rm peak}$. Note that $\gamma_{\rm peak}$ and $\nu_{\rm peak}$ are derived quantities and not input parameters.

Name	date	L' erg s^{-1}	$L_{\rm BLR}$ erg s^{-1}	$R_{\rm BLR}$ cm	B G	R cm	Γ	θ	δ	n	$\gamma_{\rm min}$	$\gamma_{\rm peak}$	$\nu_{\rm peak}$ Hz
0716 (z = 0.3)	Oct. 2000	5.0e42	0–5e42	3e17	2.5	2e16	15	3.4	16.7	3.7	5.0e2	1.8e3	5.1e14
0716 (z = 0.3)	Nov. 1998	2.7e42	0–5e42	3e17	2.5	2e16	15	3.4	16.7	3.9	4.0e2	2.0e3	6.2e14
0716 (z = 0.3)	Nov. 1996	2.2e42	0–5e42	3e17	3.0	2e16	15	3.4	16.7	3.9	5.0e2	1.5e3	4.2e14
0716 (z = 1)	Oct. 2000	4.0e43	—	—	5	2e16	15	3	18.5	3.7	1.2e3	1.2e3	5.0e14
OQ 530	Mar. 2000	8.0e41	0–5e42	2e17	2.8	1e16	10	5.0	11.4	3.9	3.3e2	2.2e3	5.8e14

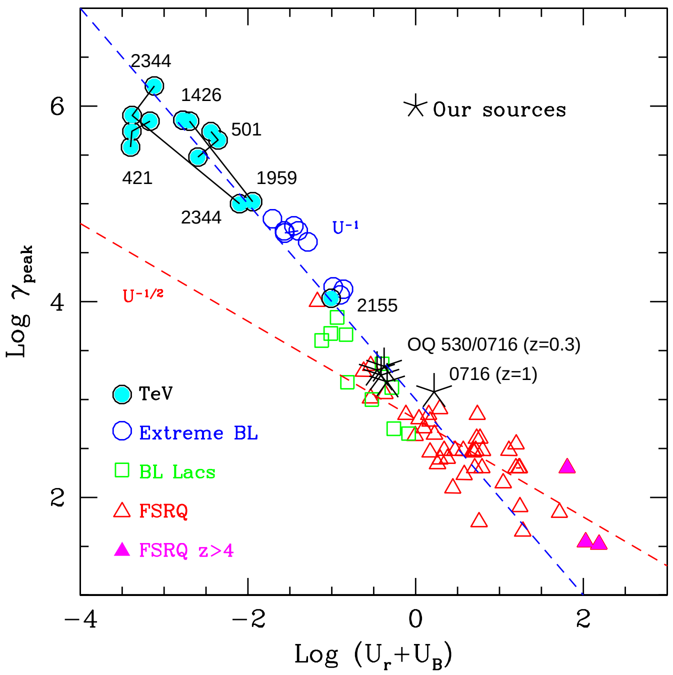

Fig. 8. Location of our sources in the $\gamma_{\rm peak}$–U plane, where U is the sum of the radiation and magnetic energy densities, as measured in the comoving frame. Note that our two sources are located in the region where the two branches (proposed by Ghisellini et al. 2002) join, supporting the intermediate nature of these two BL Lacs (for S5 0716+714 we report also one case with z = 1). Adapted from Ghisellini et al. (2002).

These should be the blazars that have the synchrotron peak in the IR-optical band and these are of course essentially LBL or intermediate blazars. In particular the two sources studied in this paper belong to the intermediate BL Lac class in terms of their spectral energy distribution. In this regard they resembles ON 231 (Tagliaferri et al. 2000): all these three BL Lacs show evidence for a concave X-ray spectrum in the 0.1–10 keV band, a signature of the presence of both the steep tail of the synchrotron emission and the flat part of the inverse Compton spectrum. Another source that we studied more than once and in which we detected both components, with a concave X-ray spectrum, or only the Compton component, is BL Lac itself (Ravasio et al. 2002). A common result that we found in ON 231, BL Lac and S5 0716+714 is that fast variability was detected for all the three sources only in the synchrotron component. This can be interpreted with the presence in the X-ray band of a Compton component (slowly variable on time scale of months), and the tail of a synchrotron component with fast and the erratic variability.

The Compton emission we see in the X-ray band is well below the Compton peak and it is produced by low energy electrons scattering low frequency synchrotron photons. The short timescale variability seen in the synchrotron part can be reproduced by changing the slope of the injected electron distribution, without affecting the total injected power. This is in line also with the fact that we do not see large shifts of the synchrotron peak frequency during our observations, that are usually performed when the source is in a higher state than the previous observations (e.g. Fig. 7, see Table 4).

In the framework of the blazar sequence proposed by Fossati et al. (1998) the two sources studied here have bolometric luminosities intermediate between HBLs (with bolometric luminosities $L \sim 10^{45}$ erg s^{-1}) and powerful broad line blazars (with bolometric luminosities up to $L \sim 10^{48}$–10^{49} erg s^{-1}, see Fig. 12 in Fossati et al. 1998). In the case of S5 0716+714, assuming z = 0.3 and a cosmology with H_0 = 65 km s^{-1} Mpc^{-1}, Ω_m = 0.3 and Ω_Λ = 0.7, the bolometric luminosity is $\sim$(3–5) $\times$ 10^{46} erg s^{-1}, while in the case of OQ 530 we have (2–10) $\times$ 10^{45} erg s^{-1}. The values of their $\gamma_{\rm peak}$ and the comoving radiation plus magnetic energy density locate our objects along the correlation found by Ghisellini et al. (1998) and Ghisellini et al. (2002), as shown in Fig. 8. Notice also that the two objects are located at the joining point between the two branches (i.e. $\gamma_{\rm peak} \propto U^{-1}$ and $\gamma_{\rm peak} \propto U^{-1/2}$) proposed by Ghisellini et al. (2002) as characterizing all blazars (we also report for comparison one case with z = 1 for S5 0716+714). Note also that the 3 states of S5 0716+714 studied here correspond to this object "moving" along the $\gamma_{\rm peak}$–U correlation, even if the small dynamic range of the variations makes this result tentative at best.

Our results show the importance of monitoring these variable sources and of performing multiwavelength observations, including an X-ray energy band as wide as possible, while they are either in a high or in weak state, to obtain the largest information on the dynamical evolution of the emission components.

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References

Abraham, R. G., McHardy, I. M., & Crawford, C. S. 1991, MNRAS, 252, 482
Aller, H. D., Aller, M. F., Latimer, G. E., & Hodge, P. E. 1985, ApJS, 59, 513
Barbieri, C., Cristiani, S., & Romano, G. 1982, AJ, 87, 616
Biermann, P. L., Duerbeck, H., Eckart, A., et al. 1981, ApJ, 247, L53
Blazejowski, M., Sikora, M., Moderski, R., & Madejski, G. M. 2000, ApJ, 545, 107
Boella, G., Butler, R. C., Perola, G., et al. 1997, A&AS, 122, 299
Cappi, M., Comastri, A., Molendi, S., et al. 1994, MNRAS, 271, 438
Comastri, A., Molendi, S., & Ghisellini, G. 1995, MNRAS, 277, 297
D'Amicis, R., Nesci, R., Massaro, E., et al. 2002, Pub. Astr. Soc. Australia, 19, 111
Dermer, C. D., & Schlickeiser, R. 1993, ApJ, 416, 458
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Fan, J. H., & Lin, R. G. 2000, ApJ, 537, 101
Fiore, F., Guainazzi, M., & Grandi, P. 1999, Cookbook for NFI *Beppo*SAX Spectral Analysis v.1.2
Fomalont, E. B., Frey, S., Paragi, Z., et al. 2000, ApJS, 131, 95
Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Ghisellini, G., Celotti, A., Fossati, G., Maraschi, L., & Comastri, A. 1998, MNRAS, 301, 451
Ghisellini, G., Celotti, A., & Costamante, L. 2002, A&A, 386, 763
Ghisellini, G., & Madau, P. 1996, MNRAS, 288, 833
Ghisellini, G., Villata, M., Raiteri, C., et al. 1997, A&A, 327, 61
Giommi, P., Barr, P., Garilli, B., Maccagni, D., & Pollock, A. M. T. 1990, ApJ, 356, 432
Giommi, P., Massaro, E., Chiappetti, L., et al. 1999, A&A, 351, 59
Giommi, P., Capalbi, M., Fiocchi, M. T., et al. 2002, in Blazar Astrophysics with BeppoSAX and other Observatories, ed. P. Giommi, E. Massaro, & G. G. C. Palumbo, ASI Special Publication, 63
Hagen-Thorn, V. A., & Marchenko, S. G. 1989, Astrophysics, 31, 551
Kühr, H. 1977, A&AS, 24, 139
Kühr, H., Witzel, A., Pauliny-Toth, I. I. K., et al. 1981, A&AS, 45, 367
Lin, Y. C., Bertsch, D. L., Dingus, B. L., et al. 1995, ApJ, 397, L5
Maraschi, L., Ghisellini, G., & Celotti, A. 1992, ApJ, 397, L5
Massaro, E., Maesano, M., Montagni, F., et al. 1999, in BL Lac Phenomenon, ed. L. O. Takalo, & A. Sillanpaa, PASP Conf. Ser., 159, 139
Massaro, E., Mantovani, F., Fanti, R., et al. 2002, in 6th European VLBI Network Symposium, ed. E. Ros, R. W. Porcas, A. P. Lobanov, & J. A. Zensus, June 25-28 2002, Bonn, Germany, 123
Miller, H. R. 1978, ApJ, 223, L67
Nesci, R., Aniello, T., Fiorucci, M., et al. 1997, Mem. Soc. Astrn. It., 68, 207
Nesci, R., Massaro, E., & Montagni, F. 2002, Pub. Astr. Soc. Australia, 19, 143
Padovani, P., & Giommi, P. 1995, ApJ, 444, 567
Padovani, P., Costamante, L., Giommi, P., Ghisellini, G., et al., MNRAS, in prep.
Ravasio, M., Tagliaferri, G., Ghisellini, G., et al. 2002, A&A, 383, 763
Rector, T. A., & Stocke, J. T. 2001, AJ, 122, 565
Scarpa, R., Urry, M. C., Falomo, R., Pesce, J. E., & Treves, A. 2000, ApJ, 532, 740
Shalinski, C. J., Witzel, A., Kirchbaum, T. P., et al. 1992, in Variability in Blazars, ed. E. Valtaoja, & M. Valtonen (Cambridge: Cambridge Univ. Press), 221
Sikora, M., Begelmann, M. C., & Rees, M. J. 1994, ApJ, 421, 153
Spada, M., Ghisellini, G., Lazzati, D., & Celotti, A. 2001, MNRAS, 325, 1559
Stickel, M., Padovani, P., Urry, C. M., Fried, J. W., & Kühr, H. 1991, ApJ, 374, 431
Stickel, M., Fried, J. W., & Kühr, H. 1993, A&AS, 98, 393
Tagliaferri, G., Ghisellini, G., Giommi, P., et al. 2000, A&A, 354, 431
Tagliaferri, G., Ghisellini, G., Giommi, P., et al. 2001, A&A, 368, 38
Urry, C. M., Sambruna, R., Worral, D. M., et al. 1996, ApJ, 463, 424
Wagner, S. J., Witzel, A., Heidt, J., et al. 1996, AJ, 111, 2187
Worrall, D. M., & Wilkes, B. J. 1990, ApJ, 360, 396
Wurtz, R., Stocke, J. T., & Yee, H. K. C. 1996, ApJS, 103, 109