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Variability of Soft X-ray Spectral Shape in Blazars Observed by ROSAT

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Abstract In paper I (Cheng et al. 2001) we have shown that the soft X-ray spectra of two types of Seyfert 1 galaxies statistically vary differently with increasing intensity. In order to understand how the spectrum of blazars changes, the spectral shape variability of 18 blazars observed by ROSAT/PSPC mode are studied by presenting the correlation of Hardness Ratio 1 versus Count Rates (HR1-CTs). According to our criteria, 10 blazars show a positive HR1-CTs relation, and only 2 blazars display an anti-correlation of HR1 versus CTs. The rest 6 blazars do not indicate any clear correlation. From these we can see that most blazars of our sample statistically show a hardening spectrum during overall flux increase, though some vary randomly. By investigating the photon index of these objects and different radiation theories, we argue that the dominance of the synchrotron or inverse Compton emission in the soft X-ray band may interpret the dichotomy of spectral variability well, and that different spectral variations might represent a sequence of synchrotron peaked frequency.

Key words: AGN: soft X-ray – variability; blazar: spectrum – polarization

1 INTRODUCTION

Blazars, including BL Lac objects, highly polarized and optically violently variable quasars, and flat-spectrum radio quasars (FSRQs), are characterized by highly variable non-thermal emission which dominates their characteristics from the radio through the γ-rays. The mechanism believed to be responsible for their broadband emission is synchrotron radiation followed by inverse Compton (IC) scattering at higher energies (e.g.

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Blandford & Konigl 1979). Relativistic beaming of a jet viewed at very small angles is the most natural explanation for the extreme properties of the class, including violent variability (up to 1-5 magnitudes in the optical; see Wagner & Witzel 1995), high γ-ray luminosities in some cases (Mukherjee et al. 1997), superluminal motion (Vermeulen & Cohen 1994), and high optical and radio polarization, sometimes extending up to 10% (Catanese & Sambruna 2000). In addition, the multiwavelength spectra of blazars usually show two peaks. The first one peaks at infrared to X-ray energies and is most probably from synchrotron radiation, which originates from electrons in a relativistic jet pointing close to the line of sight. The second peaks at γ-ray band from GeV to TeV energies and is dominated by inverse Compton emission from low-frequency seed photons (Georganopoulos 2000), which may be the synchrotron photons themselves (Sychrotron self-Compton radiation (SSC)), UV photons coming from a nearby accretion disk or from the broad-line region (Sambruna et al. 1995). However, the origin of the high energy emission is still a matter of considerable debate (e.g. Buckley 1998).

In X-rays, blazars not only exhibit large amplitude variability, but also show significant spectral variations with respect to intensity changes. For example, the spectrum of BL Lac PKS 2005-489 by ROSAT observation softens with decreasing flux (Sambruna et al. 1995). EXOSAT observations also indicate its spectral steepening during flux decrease, a behavior often displayed by other X-ray strong BL Lac objects (Sambruna et al. 1994a). What is more, a similar X-ray spectral variability trend is that their spectrum becomes harder as overall flux increases, especially during a flare state. This trend has been consistently found by Chiappeiti et al. (1999), Perlman et al. (1999), Brinkmann (2001) and Romerto et al. (2000), although in different energy bands. A possible explanation based on an inhomogeneous jet model is that spectral hardening with rising intensity is caused by either the ejection of particles into the jet or particle acceleration, and that the spectral steepening was the result of synchrotron cooling (Perlman et al. 1999; Sambruna et al. 1995).

The aim of this paper is to show what spectral variation is typical of blazars and to give some discussion or interpretation for their spectral variability. Here we present a complete spectral shape variability analysis of blazars observed by ROSAT/PSPC through the same analysis method as paper I (Cheng et al. 2001, hereafter paper I). The observations and data reduction are described briefly in Sec. 2, and our results are presented in Sec. 3. In Sec. 4 we discuss possible interpretation for different spectral variations.

2 THE OBSERVATIONS AND DATA REDUCTION

All the blazars were observed by ROSAT/PSPC mode during the periods from days to years. Besides 9 sources selected by the criteria in paper I, we selected some more blazars, including BL Lac objects with optical polarization $< 3\%$ (BLs) and high optical polar ization ($> 3\%$) blazars (HPs), from cross identification of veron (2000)'s AGN catalogue with ROSAT pointed catalog. Applying the ROSAT public archive of PSPC observations, the sources with average Count Rates (CTs) more than 0.05 s^{-1} are selected so that the error of data points is moderate. This yielded 25 blazars. The datasets are then processed for instrumental corrections and background subsection using the EXSAS/MIDAS software.

The light curve for each blazar is obtained from original ROSAT datasets with time binning of 400 seconds in three energy bands: 0.1-2.4 keV (overall band), 0.1-0.4 keV (A band), 0.5-2.0 keV (B band). Then we pick up nine of twenty-five objects by the following criteria: 1) for each source the ratio of maximal CTs to minimal CTs is greater than 2, which assures that the range of CTs variability is large enough; 2) the data points are not too scarce (> 5) and they distribute in one diagram consecutively; 3) HR1 error is small ($< 40\%$). These sources include five BLs and four HPs. Thus 18 blazars are included in our sample.

3 RESULTS OF SPECTRAL SHAPE VARIABILITY ANALYSIS

All these X-ray count rates in 0.1-2.4 keV band were gained from original ROSAT observations with time binning of 400 s. In addition, 4 energy bands are shown: A 0.1-0.4 keV, B 0.5-2.0 keV, C 0.5-0.9 keV, D 0.9-2.0 keV. The standard hardness ratios, HR1 and HR2, for ROSAT-PSPC data are defined as:

$$HR1 = \frac{B-A}{B+A}, HR2 = \frac{C-D}{C+D} \tag{1}$$

In order to describe the spectral shape variability, we present the HR1-CTs correlation for 18 blazars, as shown in Figure 1, and the results are listed in Table 1. To distinguish different variation trend of each object we fit the data through a linear formula (HR1=a+b×CTs): when the slope b is a positive or negative value and its relative error is less than 50%, we think it has a positive or negative correlation; the other instances are of random or no clear correlation. These correlations are summarized as the following:

1. For 18 blazars in our sample, ten of them which include 5 BLs and 5 HPs, show a positive HR1-CTs correlation in the sense that the spectrum hardens as the overall flux increases, in common with most of previous observations in blazars.
2. There are 6 objects, 3 BLs and 3 HPs, displaying random variation of the HR1 versus CTs relation. In other words, their spectra do not exhibit a clear softening or hardening trend with increasing flux.
3. Two exceptional sources, HP S5 1803+78 and possible BL Lac object 1207+39W4, indicate an anti-correlation of the HR1 versus CTs, implying that their spectrum steepens with rising intensity, a behavior rarely observed in blazars.

Table 1 Spectral shape variation of our selected blazars. (Positive: the HR1-CTS relation is positive, Negative: the HR1-CTS relation is negative, None: the HR1-CTS relation is random; HP: High Optical Polarization blazars (> 3%), BL: BL Lac objects with optical polarization < 3%, BL?: a possible BL Lac object; $\Gamma_{\rm rosat}$: the fitted photon index by a power law with a free neutral absorption)

Name	ROSAT name (1RXPJ)	RA (2000)	DEC (2000)	z	Type	$\Gamma_{\rm rosat}$	HR1-CTs correlation
RX J0916+52	091648+5239.3	09 16 53.5	52 38 28	0.190	BL	2.82	Positive
1E S1212+078	121510+0732.0	12 15 10.9	07 32 02	0.136	BL	2.61	Positive
PKS 2005−489	200924−4849.7	20 09 24.8	−48 49 45	0.071	BL	2.92	Positive
MS 03313−3629	033312−3619.8	03 33 12.3	−36 19 50	0.308	BL	2.38	Positive
S5 0716+71	072152+7120.4	08 41 24.4	70 53 41	0.000	BL	2.77	Positive
MS 1332−2935	133531−2950.5	13 35 30.3	−29 50 42	0.250	BL	2.10	None
2E 0336−2453	033813−2443.6	03 38 13.2	−24 43 42	0.251	BL	2.21	None
1631.9+3719	163338+3713.3	16 33 38.2	37 13 13	0.115	BL	2.84	None
1207+39W4	121026+3929.0	12 10 26.7	39 29 10	0.610	BL?	2.11	Negative
PG 1218+304	122120+3010.1	12 21 20.7	30 10 10	0.182	HP	2.21	Positive
3A 1218+303	122122+3010.5	12 21 21.9	30 10 36	0.000	HP	2.28	Positive
1E1552+2020	155424+2011.2	15 54 24.6	20 11 47	0.222	HP	1.89	Positive
3C 454.3	225357+1608.7	22 53 57.6	16 08 53	0.859	HP	1.73	Positive
3C 345.0	164258+3948.5	16 42 58.7	39 48 37	0.594	HP	1.89	Positive
B2 1215+30	121752+3006.7	12 17 52.1	30 07 00	0.000	HP	3.00	None
MS 12218+2452	122422+2436.1	12 24 22.9	24 36 11	0.218	HP	2.46	None
2E 1415+2557	141757+2543.5	14 17 57.5	25 43 35	0.237	HP	2.2	None
S5 1803+78	180042+7827.9	18 00 42.4	78 27 57	0.680	HP	2.26	Negative

4. Considering the HPs and BLs separately in Table 1, we can see that the overall photon index decreases from the BLs with a positive HR1-CTs correlation to those BLs showing random relation of HR1-CTs. On the other hand, the HPs show an opposite trend of the photon index change to the BLs: the HPs with a positive correlation to those displaying random HR1-CTS correlation exhibit a sequence of increasing soft X-ray slope. The average photon index of different subgroups is 2.70±0.21, 2.38±0.40, 2.00±0.23, 2.58±0.37 for the BLs with a positive HR1-CTs and random correlation, and the HPs showing a positive and random relation of HR1 versus CTs, respectively. It appears that the two groups, HPs and BLs, though attributed to the same class blazars, behave differently.

4 DISCUSSION AND CONCLUSIONS

The variation in the spectral index during the overall flux change can provide insights into the emission mechanism and physical conditions of the group blazars. As found previously, BL Lacs show a general hardening of the spectrum during their flares and a spectral steepening with fading intensity (Perlman et al. 1999; Sambruna et al 1995). Instead of soft X-ray photon index, here we have presented the correlation of hardness ratio versus count rates to describe the spectral variability. Among our sample, ten of eighteen blazars show a hardening spectrum during total flux enhance and 6 objects do not exhibit evident spectral variance trend or have random variations. The only two exceptions, 1207+39W4 and S5 1803+78, soften with increasing flux. These results are consistent with what have been described above. The fact that two particular objects indicate softening spectrum during the intensity increase was also observed in PKS 2155-304 by Sembay et al. (1993). Next we will discuss the implications and possible interpretations with respect to different spectral variations.

There is a general consensus that the multifrequency continuum from blazars at least up to the UV band is due to synchrotron radiation from high-energy electrons within a relativistic jet (e.g. Konigl 1989). The "curved" shape of the continuum may be due to the superposition of different emission regions with different particle spectra (inhomogeneous models), or to curvature of the particle spectrum within a single emission location or both (Ghisellini, Maraschi & Treves 1985). On the other hand, the γ-ray band is widely accepted to come from inverse Compton scattering emission based on inhomogeneous or homogenous models (Georganopoulos 2000). In terms of the X-ray band, two different radiation components share and the relative contribution varies with various blazars and different energy states (Cappi et al. 1994).

As stated above, most objects in our sample exhibit a hardening soft X-ray spectrum with increasing intensity, a behavior often displayed in other X-ray band. That might be a typical feature of the class blazars. In the framework of the inhomogeneous SSC model, Sambruna et al. (1995) have given a good fit to the broadband energy distribution of the normal BL Lac object PKS 2005-489 in its high and low state, respectively. In Fig. 5 of Sambruna et al. (1995) it is evident that the soft X-ray spectrum could be fitted well by a single synchrotron emission and becomes steeper in the low state than in the high state. In addition, the similar spectral flattening with increasing intensity can be well fitted and explained by a single IC radiation (Madejeski et al. 1999). From these, we can see that the X-ray energy spectrum of BL Lac objects consistently becomes harder during intensity rise when the energy band is dominated either by a single synchrotron emission or by IC radiation, which exactly explained the spectral hardening during the overall flux increase. Assuming the model applicable to other blazars, the main spectral variation in this paper could be well interpreted. At the same time, it suggest that the variable slope and flux of the X-rays may be due to a change in the electron distribution function in the inner part of the jet. Possible mechanism to change electron distribution is the injection of particle into the jet or in situ particle acceleration.

Besides, there are 6 objects, which show random spectral variability in the sense that the spectrum does not indicate a clear change trend with varying intensity. Two possible explanations have been proposed. The first one is that the observational span time is not suitable, which would constrain the flux and spectral variation analysis. The more probable interpretation is that the soft X-ray energy distribution of these blazars is shared by two radiative components, the synchrotron and inverse Compton emissions. According to radiation theories of blazars, two components can present different spectral steepness and variation with changing flux, and thus the blended spectrum might display a complex spectral variability though the overall intensity increases significantly. To our surprise, two particular objects in our sample showed a spectral steepening with rising intensity, a phenomenon rarely observed in blazars. Up to now there are only a few cases: spectral softening during flux increase has been seen twice in PKS 2155-304 (Sembay et al. 1993); S5 0716+714 (Giommi et al. 1999b) and AO 0235+164 (Madejeski et al. 1996) exhibited X-ray spectral steepening in their flare states. As indicated in Table 1, one of the two blazars, 1207+39W4, is still a possible BL Lac object and further identification should determine if it is a peculiar blazar. The rest one S5 1803+78, a high optical polarization source, displays the spectral variation similar to the intermediate-energy peaked BL Lacs (IBLs) S5 0716+714 and AO 0235+164. Correspondingly, as described by Perlman et al. (1999) the spectral steepening is probably because the X-ray spectrum is dominated by the very flat inverse Compton scattering radiation in the low state, but by the soft "tail" of the steep synchrotron emission in the high state.

It is interesting to note that the BLs displaying a steepening spectrum with increasing flux statistically have a steeper soft X-ray spectrum than those showing no clear spectral variation trend while the HPs indicate a trend opposite to the BLs. For blazars it is well accepted that the slope from the synchrotron radiation is much steeper than that of the IC emission, and that the X-ray energy distribution of high energy-peaked blazars is dominated by the synchrotron emission while the IC radiation prepondered the energy band for low frequency-peaked blazars (Perlman et al. 1999). Moreover, it is revealed that the blazars with low optical polarization generally show relatively high peaked frequency (Scarpa & Falomo 1997; Padovani & Gliommi 1996). As described above, the slope difference between the BLs and HPs could be interpreted below: the soft X-ray spectra of the BLs with a hardening spectrum during the overall intensity enhances are dominated by steep synchrotron radiation, in contrast, those of the HPs indicating the same spectral flattening are mainly attributed to relatively flat IC emission; for the BLs and HPs showing random spectral variations and a softening spectrum with rising intensity, the energy band at $0.1 < E < 2.4$ keV should be dominated by the combination of the synchrotron and IC radiation. Thus, the photon index of the BLs varies differently from that of the HPs from the objects exhibiting a hardening spectrum to random spectral variation during overall intensity increase. Further broad-band energy distribution analysis would give a detailed description to the two dichotomous properties.

From the discussions above, it appears that the three groups of blazars represent relative dominance of the synchrotron and IC radiation in the soft X-ray band. The BLs exhibiting a positive HR1-CTs correlation in our sample may be of the synchrotron emission preponderance and usually high-energy peaked blazars. On the contrary, the spectrum of those HPs showing an positive correlation of the HR1 versus CTs could be dominated by the flat IC radiation and they might be of low-energy peaked blazars. What is more, the soft X-ray energy distribution of the blazars whose spectrum varies randomly with rising flux is probably dominated by the mergence of the synchrotron and IC radiation, while for softening spectra that is induced by an alternation between the synchrotron and the IC radiation and their synchrotron peaked frequency would be intermediate. Consequently, it seems that from the BLs indicating a hardening spectrum through the blazars exhibiting random spectral variation or a spectral softening to the HPs showing a hardening spectrum, their synchrotron peaked frequency shifts from high to low.

In conclusion, in this paper we analyzed a complete spectral shape variability of blazars by ROSAT/PSPC observations. Most of the blazars in our sample exhibit a hardening soft X-ray spectrum with increasing flux, a typical behavior of the subclass; there are also 6 blazars which do not show any clear spectral variation trend and 2 objects display a steepening spectrum with rising intensity, a behavior rarely revealed in blazars. Based on the properties of the synchrotron and IC emissions we argue that different spectral variations might represent the relative contribution of the two components: the soft X-ray spectrum of the BLs with a hardening spectrum are dominated by the synchrotron emission while for the HPs it is dominated by the IC radiation instead; those showing random spectral variation are prepondered by the combination of the two radiations, and the steepening are prevailed by the alternation between the IC and synchrotron emissions. Thus, different soft X-ray spectral variations might correspond to a sequence of shifting synchrotron peaked frequency.

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