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

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Abstract In previous paper we have shown that the soft X-ray spectra of two types of Seyfert 1 galaxies behave statistically differently with increasing intensity. In order to see how the spectrum of blazars changes, we made plots of Hardness Ratio 1 versus Count Rates (HR1-Cts) for 18 blazars observed by ROSAT/PSPC. According to our criteria, ten showed a positive HR1-Cts correlation, two a negative correlation, and the remaining six, no clear correlation. Thus, most blazars of our sample 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 relative dominance between the synchrotron and inverse Compton emission in the soft X-ray band can well account for the differing spectral behaviours and that the different spectral variations might represent a sequence of synchrotron peaked frequency.

Key words: galaxies: active — galaxies: X-ray — blazar: spectrum

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 radio to γ-ray bands. The mechanism believed to be responsible for their broadband emission is synchrotron radiation followed by inverse Compton (IC) scattering at higher energies (e.g. 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; the second peaks at γ-ray band from GeV to TeV energies and is dominated by inverse Compton emission from low-frequency seed photons (Georganopou-

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los 2000). More interestingly, Fossati et al. (1998) revealed that the two peak frequencies are correlated and that the luminosity ratio between the high and low frequency components increases with bolometric luminosity. However, the origin of the high energy emission is still a matter of considerable debate (e.g. Buckley 1998).

In X-rays, the 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 of the same object also indicate a spectral steepening during flux decrease, a behavior often displayed by other X-ray-loud BL Lac objects (Sambruna et al. 1994a). Furthermore, a similar X-ray spectral variability trend is that their spectrum becomes harder as the overall flux increases, especially during a flare period. 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 by particle acceleration, and that the spectral steepening is the result of synchrotron cooling (Perlman et al. 1999; Sambruna et al. 1995).

In addition to the variability in the high-energy band, blazars show rapid variation in low-energy bands. Optical monitoring indicates that γ-ray−loud blazars have a typical minimum variability timescale about 1 hour (Xie et al. 1999; Villata et al. 1997). Moreover, Xie et al. (2001) found that the TeV γ-ray emission of Mrk 501 correlated with its optical emission by analyzing the relationship between the optical and γ-ray variabilities. All of these findings will provide strong constraints on emission models.

The aim of this paper is to find out what spectral variation is typical of blazars and to discuss and interpret any such variability. We shall give a complete analysis of spectral shape variability in the blazars observed by ROSAT/PSPC using the same method of analysis as Cheng et al. (2001, hereafter paper I). The observations and data reduction are described briefly in Sec. 2. Our results are presented in Sec. 3. In Sec. 4 we discuss possible interpretations for different spectral variations.

2 OBSERVATIONS AND DATA REDUCTION

All the blazars were observed in ROSAT/PSPC mode over periods varying from days to years. Besides nine sources selected by the criteria in paper I, we selected some more, including BL Lac objects with optical polarization $< 3\%$ (BLs) and high optical polarization ($> 3\%$) blazars (HPs), from cross identification of véron (2000)'s AGN catalogue with ROSAT point source catalog. From the ROSAT public archive of PSPC observations, only sources with average Count Rates (Cts) greater than 0.05 s^{-1} were selected so as to keep the statistical error moderate. This yielded 25 blazars. The datasets were then processed for instrumental corrections and background subtraction using the EXSAS/MIDAS software.

The light curve for each blazar is obtained from the original ROSAT datasets in 400-second time bins 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). We then pick out nine of the twenty-five objects by the following criteria: 1) for each source the ratio of maximal Cts to minimal Cts is greater than 2, which ensures that the range of Cts variability is large enough; 2) the data points are not too few (> 5) and they are distributed with no large gaps; 3) their HR1 error is small ($< 40\%$). These nine sources include five BLs and four HPs. Thus our sample contains a total of 18 blazars.

3 RESULTS OF SPECTRAL SHAPE VARIABILITY ANALYSIS

All the X-ray count rates in the 0.1–2.4 keV band were taken from original ROSAT observations with time binning of 400 s. In addition, four 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

$$\mathrm{HR1} = \frac{B-A}{B+A}, \mathrm{HR2} = \frac{C-D}{C+D}. \quad (1)$$

Table 1 Spectral Shape Variation of Our Selected Blazars

Name	ROSAT name (1RXPJ)	RA (2000)	DEC (2000)	z	Type	Γ_{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

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; Γ_{rosat}: the fitted photon index by a power law with a free neutral absorption.

In order to describe the spectral shape variability, we present in Figure 1 the HR1-Cts correlation for 18 blazars. Our results are given in Table 1. To distinguish different variation trends we fit the data with a linear formula (HR1=a+b×Cts): when the slope b has a positive or negative value with relative error less than 50%, then we regard it to have a positive or negative correlation; otherwise we regard the variation to be random. These correlations are summarized as follows:

1. For the 18 blazars in our sample, ten comprising five BLs and five 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 six objects, three BLs and three HPs, displaying random variation in 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, show a negative correlation between HR1 and Cts, implying that their spectrum steepens with rising intensity, a behavior rarely observed in blazars.

4. Consider separately the BLs and HPs in Table 1. For the BLs, we can see that the overall photon index decreases from the BLs with a positive HR1-Cts correlation to those BLs showing a random relation. On the other hand, the HPs show an opposite trend: the soft X-ray slope increases from those HPs with a positive correlation to those displaying a random correlation. The average photon indices of the four groups are 2.70±0.21, (BLs, positive correlation), 2.38±0.40 (BLs, random), 2.00±0.23 (HPs, positive), and 2.58±0.37 (HPs, random). 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 as the overall flux changes can provide insights into the relevant emission mechanism and physical conditions. 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). In the optical band, Fan et al. (1998) also found the same spectral variability trend as in the X-ray and γ-ray. Instead of the soft X-ray photon index, here we have used the correlation between the hardness ratio and the count rates to describe the spectral variability. Among our sample of 18 blazars ten show a hardening spectrum with increasing total flux and six exhibit no evident trend other than random. 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 uncommon feature of a softening spectrum with increasing intensity, shown by the two exceptions, was also observed in PKS 2155–304 by Sembay et al. (1993). Next we will discuss the implications and possible interpretations of the different spectral variations.

There is a general consensus that the multifrequency continuum of 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). For the X-ray band, the two different radiation components are both present and the relative contribution varies with different blazars and different energy states (Cappi et al. 1994).

As mentioned above, most objects in our sample exhibit a hardening soft X-ray spectrum with increasing intensity, a behavior often displayed in other X-ray bands. That might be a typical feature of the class blazars. In the framework of the inhomogeneous SSC model, Sambruna et al. (1995) gave a good fit to the broadband energy distribution of the normal BL Lac object PKS 2005–489 both in its high and low state. In figure 5 of Sambruna et al. (1995) it is evident that the soft X-ray spectrum could be fitted well by a single synchrotron

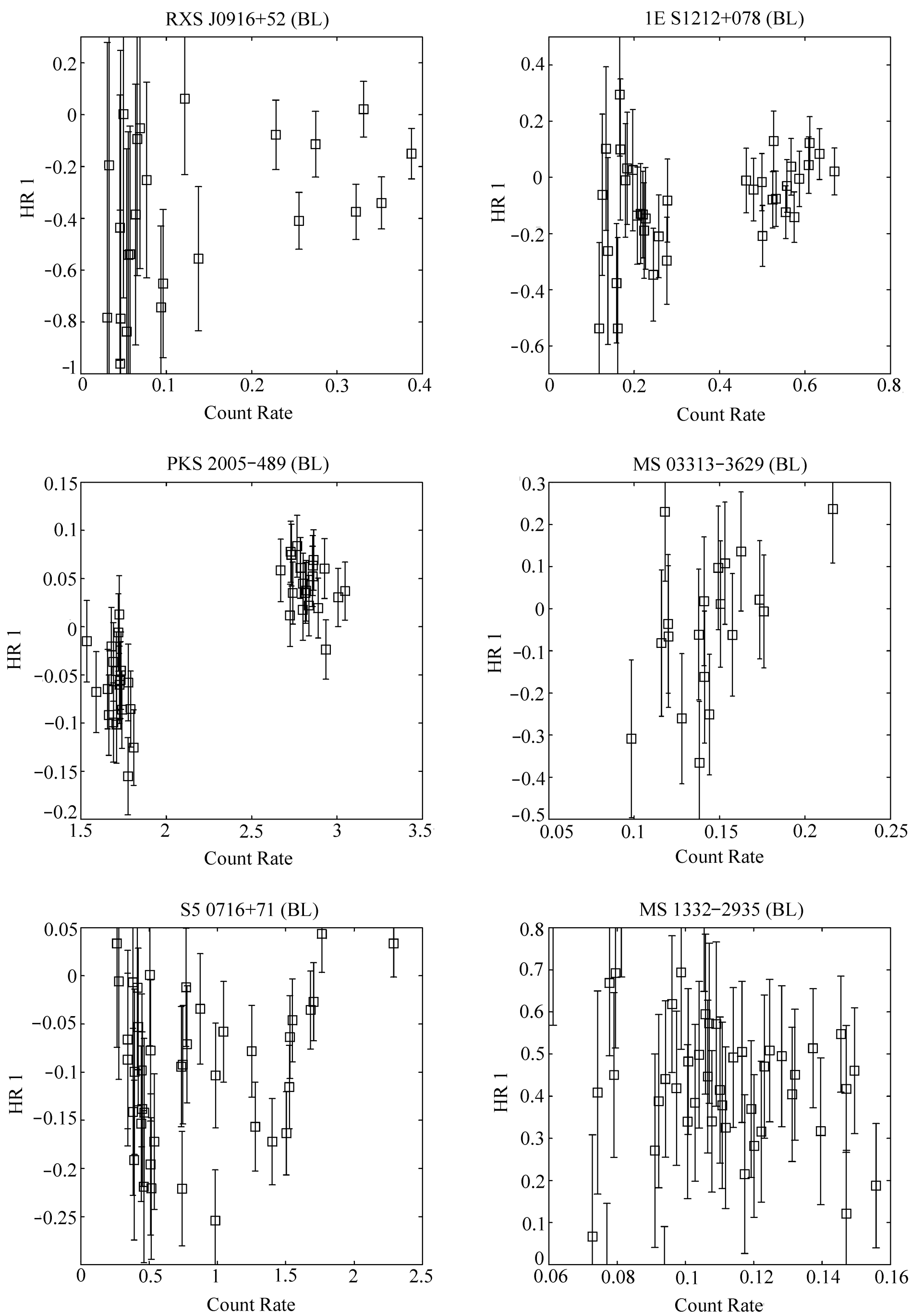

Fig. 1 Hardness Ratio versus overall count rates (0.1–2.4 keV)

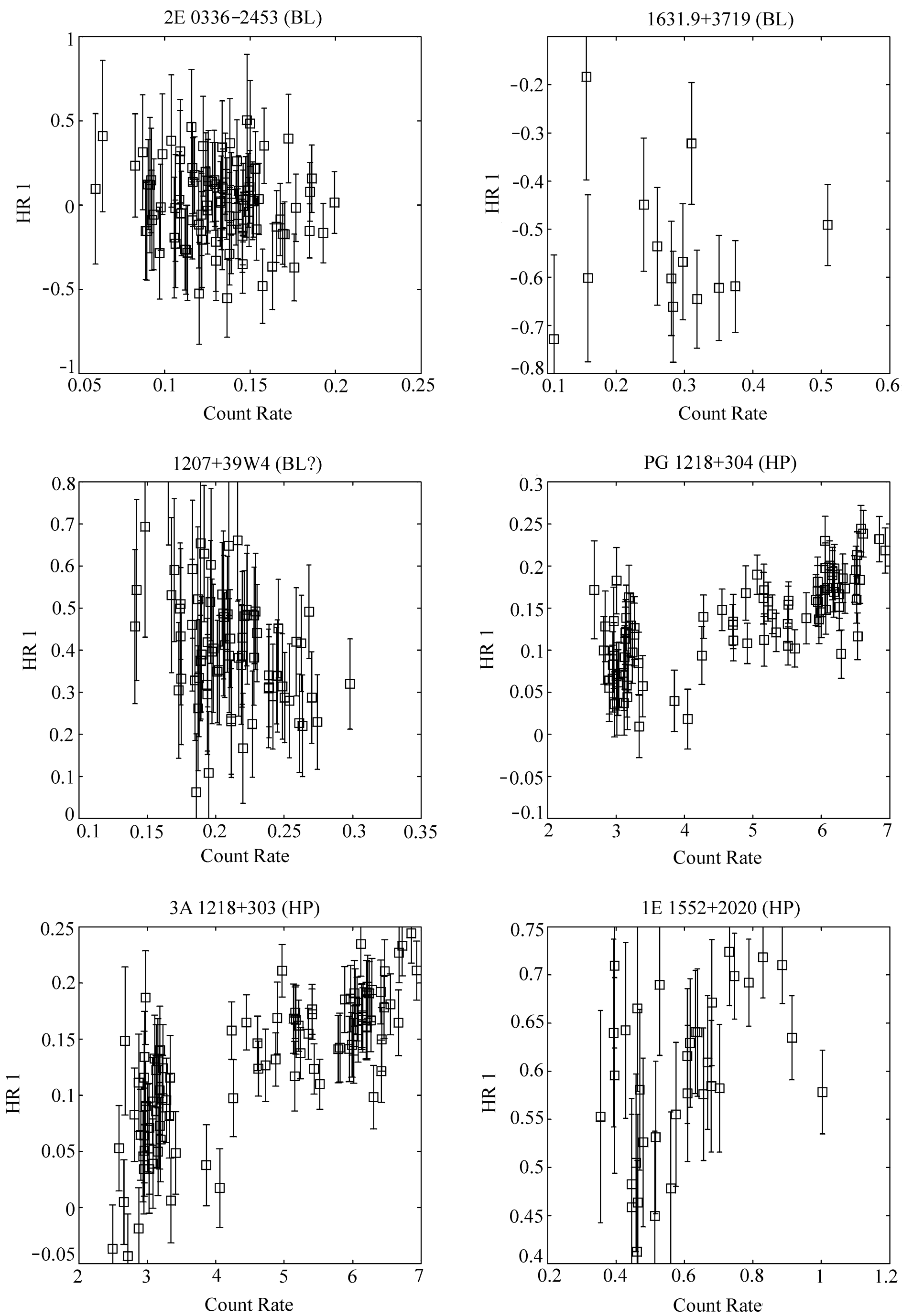

Fig. 1 Continued

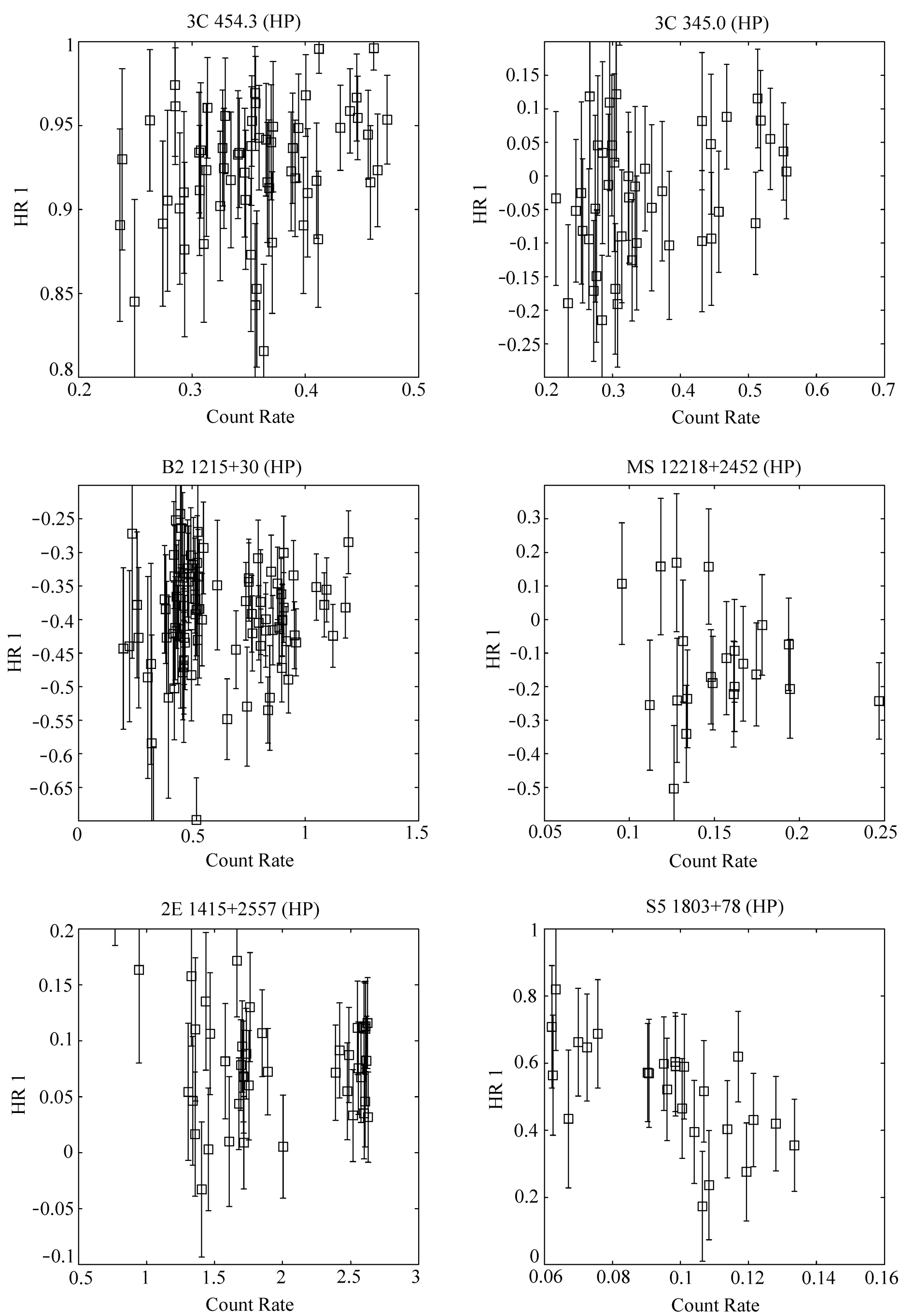

Fig. 1 Continued

emission power law which is 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 with overall flux increase. If we assume the model applicable to other blazars, then the main spectral variation in this paper could be well interpreted. At the same time, it suggests 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. A possible mechanism to change the electron distribution is an injection of particles into the jet or an in situ particle acceleration.

Besides, there are six objects which show random spectral shape variability in the sense that the spectrum does not indicate a clear trend with varying intensity. Two possible explanations have been proposed. The first one is that the observational time span 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 the radiation theories of blazars, the two components can present different spectral behaviours with respect to flux changes, so the blended spectrum might display a complex spectral variability when 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 such cases: spectral softening during flux increase has been seen twice in PKS 2155-304 (Sembay et al. 1993); while 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 remaining 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. Perlman et al. (1999) wrote that the spectral steepening is probably because the X-ray spectrum is dominated by the very flat inverse Compton scattering radiation in the low state, and 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 preponderated 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 higher peak frequencies (Scarpa & Falomo 1997; Padovani & Gliommi 1996). Fossati et al. (1998) also found the trend that with increasing luminosity both the synchrotron peak and the inverse Compton peak move to lower frequencies and that the latter becomes energetically more dominant.

As described above, the slope difference between the BLs and HPs could be interpreted as follows: 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 a relatively flat IC emission; for the BLs and HPs showing random spectral variations and a softening spectrum with rising intensity, the energy band at $0.1 < E < 2.4\,\mathrm{keV}$ should be dominated by a combination of the synchrotron and IC radiation. Thus, the photon index of the BLs varies differently from that of the HPs as we move from objects exhibiting a hardening spectrum to those showing random variation with increasing intensity. Further broad-band energy distribution analysis would give a detailed description to the two contrasting behaviours.

From the discussions above, it appears that the three groups of blazars are distinguished by the 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 have predominant synchrotron emission and are usually high-energy peaked blazars. In contrast, the spectrum of those HPs showing the same positive HR1–Cts correlation could be dominated by the flat IC radiation and they might be low-energy peaked blazars. Moreover, the soft X-ray energy distribution of the blazars whose spectrum varies randomly with rising flux is probably dominated by a merged synchrotron and IC radiation, while the softening spectra are 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 with a hardening spectrum through the blazars exhibiting random spectral variation or a spectral softening to the HPs showing a hardening spectrum, the synchrotron peaked frequency shifts from high to low.

In conclusion, we have made a complete analysis of spectral shape variability of blazars in the ROSAT/PSPC observations. Most of the blazars in our sample exhibit a typical hardening soft X-ray spectrum with increasing flux; there are also six blazars which do not show any clear spectral variation trend and two objects which display a steepening spectrum with rising intensity, a behavior rarely found in blazars. Based on the properties of the synchrotron and IC emissions we argue that the different spectral variations might represent different relative contributions 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 preponderated by a combination of the two radiations, and the steepening spectrum, by an 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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References

Blandford R., Konigl A., 1979, ApJ, 232, 34
Brinkmann W., Sembay S., Griffiths R. et al. 2001, A&A, 365, L162
Buckley J. H., 1998, Science, 279, 676
Cappi M., Comastri A., Molendi S. et al. 1994, MNRAS, 271, 438
Catanese M., Sambruna R. M., 2000, ApJ, 534, L39
Cheng L. P., Wei J. Y., Zhao Y. H., 2001, submitted to A&A (astro-ph/0110569)
Chiappeiti L., Maraschi L., Tavecchio F. et al., 1999, ApJ, 521, 552
Fan J. H., Xie G. Z., Pecontal E. et al., 1998, ApJ, 507, 173
Fossati G., Maraschi L., Celotti A. et al., 1998, MNRAS, 299, 433

Georganopoulos M., 2000, ApJ, 543, L15
Ghisellini G., Maraschi L., Treves A., 1985, A&A, 146, 204
Giommi P., Massaro E., Chiappetti L. et al., 1999, A&A, 351, 59
Konigl A., 1989, In: Maraschi L., Maccacaro T., Ulrich M.-H., eds., BL Lac objects, Berlin: Springer, 321
Madejeski G. M., Takahashi T., Tashiro M. et al., 1996, ApJ, 459, 156
Madejeski G. M., Sikora M., Jaffe T. et al., 1999, ApJ, 521, 145
Mukherjee R., Bertsch D. L., Bloom S. D. et al., 1997, ApJ, 490, 116
Perlman E. S., Madejski G., Stocke J. T. et al., 1999, ApJ, 523, L11
Padovani P., Giommi P., 1996, MNRAS, 279, 526
Romerto G. E., Cellone S. A., Combi J. A., 2000, A&A, 360, L47
Sambruna R. M., Rita M., Barr P. et al., 1994a, ApJ, 434, 468
Sambruna R. M., Urry C. M., Ghisellini G. et al., 1995, ApJ, 449, 567
Scarpa R., Falomo R., 1997, A&A, 325, 109
Sembay S., Warwick R. S., Urry C. M. et al., 1993, ApJ, 404, 112
Wagner S. J., Witzel A., 1995, ARA&A, 33, 163
Vermeulen R., Cohen M., 1994, ApJ, 430, 467
Villata M., Raiter C. M., Ghisellini G. et al., 1997, AAS, 121, 119
Xie G. Z., Li K. H., Zhang X. et al., 1999, ApJ, 522, 846
Xie G. Z., Li K. H., Bai J. M. et al., 2001, ApJ, 548, 200