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Spectral Evolution of Synchrotron and Inverse Compton Emission in BL Lac Objects

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Abstract. With XMM–Newton observations, the X-ray spectral variations and the derived physical implications for two very high energy gamma-ray BL Lac objects PKS 2155–304 and S5 0716+714 are presented.

Key words. BL Lacertae objects—galaxies: active—X-rays: galaxies.

1. Introduction

Blazars are currently classified on the basis of peak energy locations of the synchrotron emission component in spectral energy distributions (SEDs). BL Lac objects are differentiated into high-energy-peaked BL Lac objects (HBLs) and low-energy-peaked BL Lac objects (LBLs), whose synchrotron emission SEDs peak in the UV/X-ray and in the IR-optical wavelengths, respectively.

In X-rays, HBLs are strongly variable and show steep ($\Gamma > 2$) spectra which are convex-shaped or continuously steeper with higher photon energies (e.g., Tramacere *et al.* 2007). The X-ray emission of HBLs is thus interpreted as synchrotron radiation from the high-energy tail of an electron distribution, which is sensitive to particle acceleration and cooling, and strong variations and steep spectra are expected. Nevertheless, LBLs are variable in soft X-rays but much less variable in hard X-rays. At the same time, the soft X-ray spectra of LBLs are steep ($\Gamma > 2$) but their hard X-ray spectra are flat ($\Gamma < 2$), indicating that the X-ray spectra of LBLs are concave-shaped. Therefore, the soft X-ray emission of LBLs are thought to be dominated by synchrotron emission from the high-energy tail of an electron distribution, whereas inverse Compton (IC) emission of the low-energy electrons of the same electron distribution scattering synchrotron (and/or external in some cases) photons to higher energies contributes more in the hard X-rays (e.g., Giommi *et al.* 1999).

PKS 2155–304 is classified as an HBL, its synchrotron emission was found to peak in the UV rather than in the X-ray range (Zhang *et al.* 2002; Massaro *et al.* 2008). S5 0716+714 is identified as a prototype of LBLs since its synchrotron emission peaks in the optical band (e.g., Nieppola *et al.* 2006). In order to understand the evolution of synchrotron and IC spectra of BL Lac objects, the X-ray spectral analysis with XMM–Newton X-ray observations of PKS 2155–304 and S5 0716+7145 (see Zhang 2008, 2010 for details) was performed. Here, the results and the implications are presented.

2. PKS 2155–304

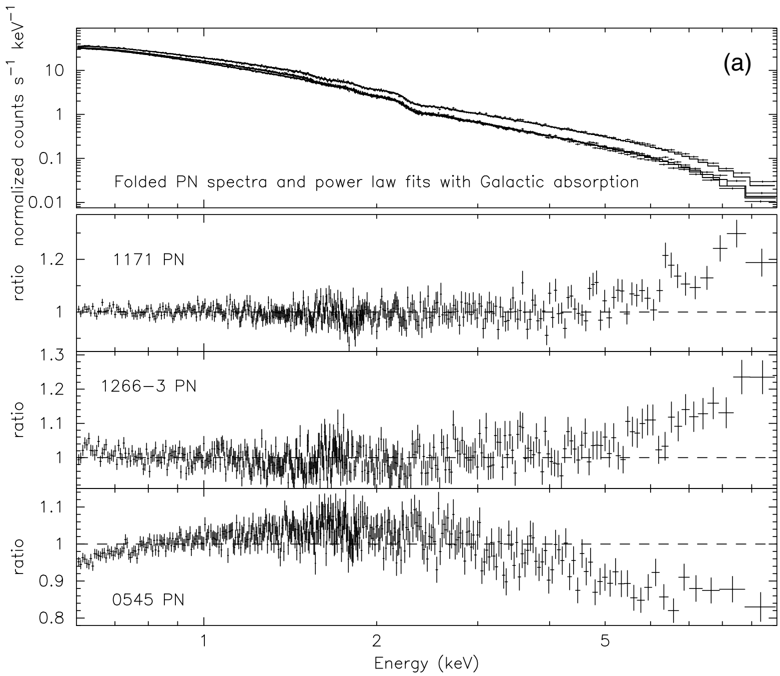
As a calibration target, XMM–Newton repeatedly monitored PKS 2155–304 since 2000. The most interesting result obtained with these observations is that the 0.6–10 keV X-ray spectral shapes of PKS 2155–304 were concave when it was in relatively low brightness state in 2006, which is opposite to the normal convex-shaped X-ray spectra of the source. Nevertheless, the X-ray spectra during all other observations were still convex. Figure 1(a) shows the data-to-model ratios (the second and third panels) by fitting, the count spectra (the first panel) with a single power-law for May 1 2006 and November 7 2006 observations, clearly suggesting that the spectra hardens above $\sim$4 keV. As a comparison, the fourth panel in the same plot also shows the data-to-model ratios by fitting November 29 2002 count spectrum with a single power-law, indicating a convex spectrum typical of HBLs. When fitting the two 2006 spectra with a broken power-law, it was found that the spectra hardened ($\Delta\Gamma \sim 0.3$) at break energies of $\sim$4 keV. However, it is worth noting, though PKS 2155–304 showed concave X-ray spectra similar to those of LBLs, but its hard X-ray spectra are still steep ($\Gamma > 2$), which is different from those of LBLs (see section 3 for S5 0716+714). Similar to LBLs, the concave X-ray spectra of PKS 2155–304 could be interpreted as a mixture of steep high energy tail of the synchrotron emission and a flat low-energy side of the IC emission. However, the steep hard X-ray spectra indicated that the synchrotron component still dominates over the IC one, though the latter is effectively presented and perceived as hardening the synchrotron spectrum. This is the first evidence for a HBLs showing IC signature in the X-ray band.

Figure 1(b) plots the simultaneous optical/UV/X-ray SEDs obtained with XMM–Newton. One can see that the concave X-ray spectra observed in 2006 might be the result of downward shift of the synchrotron peak energy to the optical range, causing IC emission to become more important in the hard ($>\sim$4 keV) X-ray band with respect to the one in 2002 in which the synchrotron emission still peaks in the UV to soft X-ray range.

3. S5 0716+714

S5 0716+714 was observed by XMM–Newton on September 24–25 2007, lasting $\sim$74 ks. The source showed strong variations. In order to explore spectral evolution of its synchrotron and IC emission components, the whole observation was divided into several intervals according to the time order and count rate level. The observed count spectra were fitted with a double power-law model for the purpose of disentangling the two emission components. The steep power-law represents the high energy tail of synchrotron component, and the flat one is for the low energy side of the IC component.

Figure 2(a) shows a relationship between photon indices and 0.5–10 keV fluxes for the synchrotron component, Fig. 2(b) gives the relationship between photon indices and the 0.5–10 keV fluxes for the IC component, and Fig. 2(c) the synchrotron and IC 0.5–10 keV fluxes are plotted against the total (i.e., synchrotron plus IC) 0.5–10 keV fluxes, respectively. The results can be summarized as follows. The synchrotron spectra appear to harden with larger synchrotron fluxes, whereas the IC spectra seem to soften with larger IC fluxes. When the total fluxes increase, it appears that the



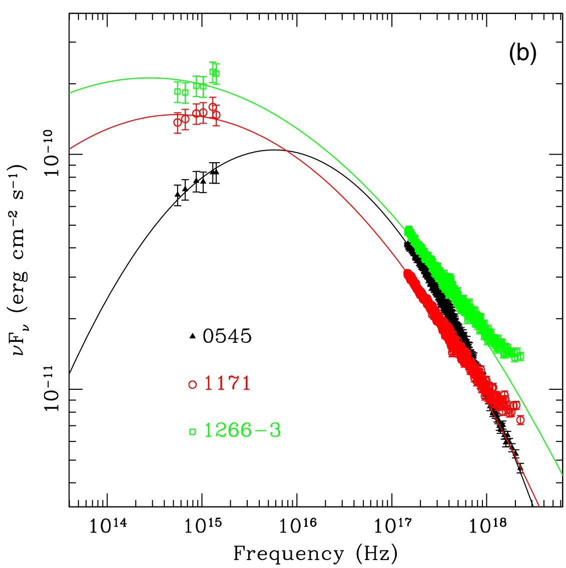


Figure 1. For PKS 2155–304. **(a)** The first panel presents the pn count spectra of May 1 2006 (orbit 1171), November 7, 2006 (orbit 1266-3) and November 29, 2002 (orbit 0545), and the respective best power-law fit model. The data-to-model ratios (2–4 panels) clearly show concave spectra for orbits 1171 and 1266-3, and convex spectrum for orbit 0545. **(b)** Simultaneous optical/UV/X-ray SEDs obtained with XMM–Newton for the same three epochs as **(a)**. The solid lines are the best parabolic fits to the data between the optical and 2 keV range, which is then extrapolated to 10 keV. For orbits 1171 and 1266-3, the deviations of the hard X-ray SEDs from the synchrotron SEDs (i.e., the parabola) suggest possible emergence of the IC component. These plots are taken from Zhang (2008).

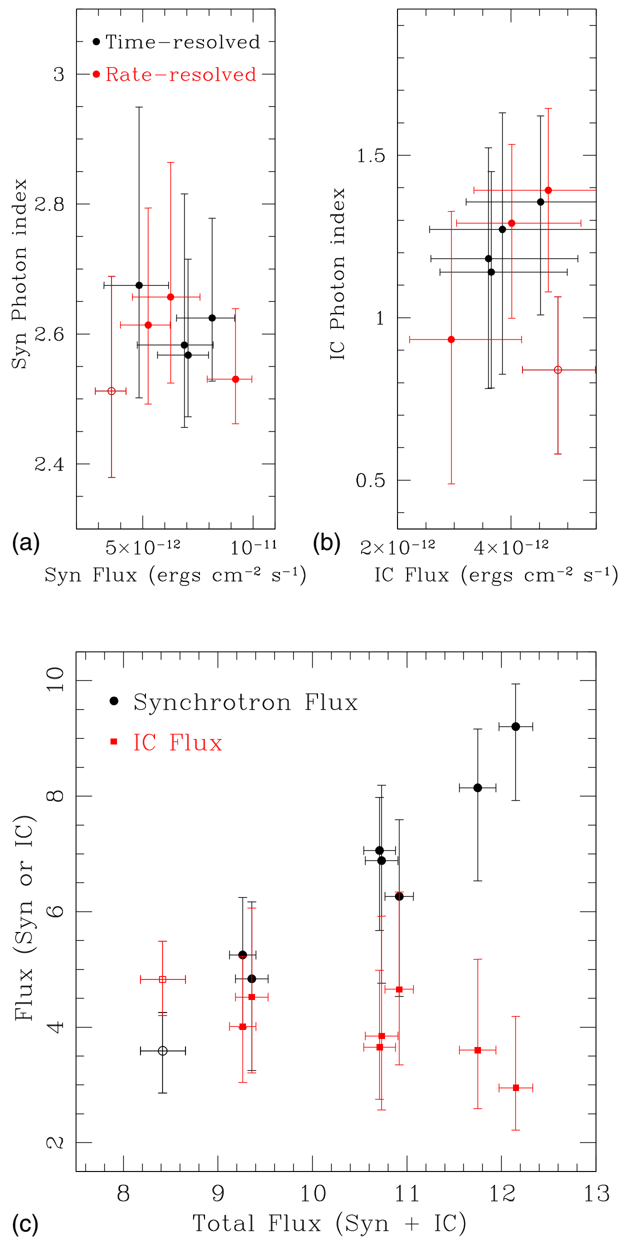


Figure 2. For S5 0716+714. **(a)** Relationship between photon indices and 0.5–10 keV fluxes for synchrotron (Syn) component, **(b)** presents relationship between photon indices and 0.5–10 keV fluxes for the IC component, and **(c)** gives synchrotron (Syn) and IC 0.5–10 keV fluxes against the total (synchrotron plus IC) 0.5–10 keV fluxes (the fluxes are in units of 10^{-12}erg cm^{-2}s^{-1}). The open symbol indicates the interval which is affected by the high background. These plots are taken from Zhang (2010).

synchrotron fluxes increase but the IC fluxes decrease. The synchrotron component exhibits larger flux variations but does smaller spectral changes than the IC component. The X-ray spectral evolution demonstrates that the synchrotron and IC SED peaks of S5 0716+714 shift to higher energies with higher fluxes, causing lower energy and flatter side of the IC component which comes forth in the observed X-ray range.

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