ASCA Observations of the BL Lacertae Object OJ 287

in 1997 April and November

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Abstract

X-ray properties of the BL Lacertae object OJ 287, observed with ASCA on 1997 April 26 and November 17, are reported. The 0.5 – 10 keV flux was lower than those obtained in previous X-ray observations, and no evidence of intensity variations was found during each observation. The obtained flux densities at 1 keV, 0.22 ± 0.26 µJy, exceed the extrapolations from lower frequency synchrotron continua, which were measured in nearly the same period as the present ASCA observations. The X-ray spectra acquired with the GIS and SIS were consistently described with a single power law model modified with the Galactic absorption, and the derived photon indices, 1.5 ~ 1.6, are flatter than those observed so far. These results strongly suggest that the X-ray spectra observed in 1997 arise via inverse Compton process alone. The X-ray spectra obtained in 1994 (Idesawa et al 1997), exhibiting a steeper slope than those in 1997, is thought to be contaminated by "synchrotron soft tail".

Key words: galaxies: BL Lacertae objects: individual (OJ 287) — X-rays: general
1. Introduction

Blazars, including BL Lacertae objects and Optical Violently Variable (OVV) quasars, are a class of active galactic nuclei of which the spectrum is dominated by nonthermal radiation from relativistic electrons in jets pointing at us (e.g. Blandford, Rees 1978; Blandford, Königl 1979). Their multi-frequency spectra exhibit two pronounced components. According to the unified model of blazars, the low energy component arises via synchrotron radiation (SR), and the high energy one via inverse-Compton (IC) scattering by the same population of electrons that produce the SR component. Seed soft photons for the IC scattering can be either the SR photons themselves (so-called synchrotron-self-Compton process; Maraschi, Ghisellini, Celloti 1992; Bloom, Marsher 1996), ultraviolet photons from the accretion disk (e.g. Dermer, Schlickheiser, Mastichiadis 1992) or from emission line cloud (Sikora, Begelman, Rees 1994; Blandford, Levinson 1995), or infrared photons ambient to the host galaxy (Sikora et al. 1994).

There are two extreme subclasses of blazars (Sambruna, Maraschi, Urry 1996; Giommi, Ansali, Micol 1995; Fossati et al. 1998). One of them, high-energy peaked BL Lac objects (HBLs; Padovani, Giommi 1996), have the SR peak in the ultraviolet to soft X-ray band. Their X-ray emission is dominated by the SR component as evidence by steep spectral slopes with photon index $\Gamma = 2.0 \sim 3.0$ (e.g. Kubo et al. 1998). The other, OVV quasars, show the SR peak in the millimeter to optical range, and their X-ray emission is dominated by the IC component with relatively flat spectral slopes with $\Gamma \sim 1.5$ (Kubo et al. 1998).

Yet, another subclass of blazars called low-energy peaked BL Lac objects (LBLs; Padovani, Giommi 1996) exhibit spectral properties intermediate between those of HBLs and OVV quasars (Sambruna, Maraschi, Urry 1996; Giommi, Ansali, Micol 1995; Fossati et al. 1998). In their spectra, the SR and IC components are thought to compete in the ultraviolet to X-ray bands, resulting in X-ray slopes of $\Gamma = 1.5 \sim 2.0$ (Kubo et al. 1998). In order to disentangle interplay between the SR and IC components, and to examine the two component interpretation of the blazars emission, extensive X-ray observations of LBLs have been carried out (e.g. Urry et al. 1996; PKS 0735+178, Madejski, Schwartz 1988; PKS 0521-365, Garilli, Maccagni 1990; BL Lacertae itself, Kawai et al. 1991; AO 0235+164, Madejski et al. 1996). However, there are only a few LBLs of which the X-ray spectra have been decomposed unambiguously into the two components.

OJ 287, at a redshift of $z = 0.306$ (Stickel et al. 1989), is one of the most extensively observed BL Lac objects. It exhibits large intensity and polarization variability in various energy bands, together with superluminal motion.
(Gabuzda et al. 1989). Its multi-frequency continuum is smoothly distributed from radio to ultraviolet bands, with a SR peak at \( \sim 5 \times 10^{13} \) Hz and radio to X-ray spectral index of \( \alpha_{rX} \sim 0.84 \) (Sambruna, Maraschi, Urry 1996); these make OJ 287 a typical LBL (Padovani, Giommi 1995). In X-rays, relatively steep spectra were obtained with Einstein, EXOSAT and ROSAT in 1979 – 1980 (Madejski, Schwartz 1988), 1983 – 1984 (Sambruna et al. 1994) and 1991 (Comastri, Nolendi, Ghisellini 1995; Urry et al. 1996), respectively. However, the Ginga observations performed in 1989 – 1990 (Ohashi 1989; Tashiro 1994) failed to detect X-rays from this object. The X-ray intensity varied by a factor of 3 on time scales of months (Madejski, Schwartz 1988), and 30% within 3 days (Pollock et al. 1985). The X-ray spectra obtained with the Einstein IPC, smoothly connecting to the lower energy continua (Madejski, Schwartz 1988), is considered to arise from the SR process. Giommi et al. (1995), however, detected a hint of X-ray excess above extrapolation from the optical-to-ultraviolet continua. This suggests the presence of an additional IC component in the X-ray emission from this LBL.

In 1994, an optical outburst of OJ 287 motivated a series of worldwide multi-band observations including an ASCA observation. However, the measured X-ray flux was the lowest among the X-ray results reported so far (Idesawa et al. 1997; paper I). Moreover, the obtained X-ray spectra, exhibiting the hardest record, did not smoothly connect to the low energy continuum. As argued by Idesawa et al. (paper I), this reinforce the presence of the underlying IC component in the ASCA X-ray spectra, although they could not unambiguously resolve the suggested IC component from the SR component. In order to better resolve the two components, it is important to measure long-term spectral and intensity changes of this object, where the two emission components are expected to vary independently to a first approximation. Accordingly, two separate ASCA observations were conducted in 1997.

2. Observations and Results

2.1. Observation and Data Reduction

The ASCA observations of OJ 287 were performed on 1997 April 26 and on 1997 November 18. The GIS (Gas Imaging Spectrometer; Ohashi et al. 1996; Makishima et al. 1996) and the SIS (Solid-state-Imaging-Spectrometer; Burke et al. 1991; Gendreau et al. 1993; Yamashita et al. 1997) were operated in normal PH mode and 1CCD FAINT mode, respectively. The target source was placed on the 1CCD nominal position of SIS0 chip1 and SIS1 chip3. The source was significantly detected at the position which coincides with the optical counterpart, and the
image was consistent with that from a point source within the accuracy of the ASCA point spread function. There is no other confusing X-ray sources in the field of view of the GIS or SIS. Data screening was carried out in the standard manner, yielding $\sim 4 \times 10^4$ s of exposure from each observation.

2.2. X-ray Light Curve

The average 0.5–10 keV source count rates obtained with the GIS (GIS2+GIS3) and the SIS (SIS0+SIS1), together with statistical errors (1σ), were $(2.65 \pm 0.07) \times 10^{-2} \text{ c s}^{-1} \text{ GIS}^{-1}$ and $(4.15 \pm 0.09) \times 10^{-2} \text{ c s}^{-1} \text{ SIS}^{-1}$ on April 26, and $(3.23 \pm 0.07) \times 10^{-2} \text{ c s}^{-1} \text{ GIS}^{-1}$ and $(5.28 \pm 0.09) \times 10^{-2} \text{ c s}^{-1} \text{ SIS}^{-1}$ on November 18, respectively. These are about one third of those obtained with the ASCA observation in 1994 (paper I).

In Figure 1, the summed GIS+SIS light curves are shown in the 0.5–2 keV and 2–10 keV bands. The background was not subtracted, but is estimated to be less than 15 % of the total count rate in each bin. These light curves appear to exhibit intensity variations on time scale of a few hours in each observation. However, a chi-square test examining a constant count rate hypothesis gives $\chi^2 = 21.4$ and 6.1 for 16 degrees of freedom in the hard and soft bands, respectively, for the April observation; $\chi^2 = 10.9$ and 14.9 for 15 degrees of freedom for the November observation. Therefore the short-term variation is concluded to be statistically insignificant.

2.3. X-Ray Spectra

In the following analysis, the X-ray signals are integrated within the circular regions centered on the source position, with the 3′ radii for both detectors. The background spectra were accumulated over a source free region of the same observation with the same radius. Figure 2 shows the background subtracted GIS (GIS2+GIS3) and SIS (SIS0+SIS1) spectra of OJ 287 without removing the instrumental response. Errors of these spectra represent photon statistics. Thus, the signal X-ray were detected over the 0.6-7 keV range with the SIS, and 0.8-10 keV range with the GIS.

The obtained spectra are quite featureless. A single power-law model modified with the photoelectric absorptions was examined against the data, where the column density is fixed at the Galactic value, $N_H = 2.75 \times 10^{20} \text{ cm}^{-2}$ (Elvis et al. 1989). Then, both the GIS and SIS spectra were described successfully with this model, and the derived best-fit parameters, summarized in table 1, are consistent between the two detectors. Accordingly, the GIS and SIS spectra were fitted simultaneously, which was also successful (see table 1). The derived photon indices are
\[ \Gamma = 1.57 \pm 0.09 \text{ for April and } \Gamma = 1.51 \pm 0.09 \text{ for November observations. These values are harder than those reported from the previous observations, such as } \Gamma = 1.5 \sim 2.3 \text{ with Einstein (Madejski, Schwartz, 1988), } \Gamma = 2.16 \sim 2.37 \text{ with EXOSAT (Sambruna et al. 1994), } \Gamma = 2.16 \sim 2.60 \text{ with ROSAT (Comastri et al. 1995; Urry et al. 1996), and } \Gamma = 1.67 \pm 0.02 \text{ with ASCA in 1994 (paper I). The derived flux densities at 1 keV are } 0.22 \pm 0.01 \mu \text{Jy for April and } 0.25 \pm 0.02 \mu \text{Jy for November (see table 1). These values are lower than those obtained on previous occasions, such as } 0.94 \sim 2.70 \mu \text{Jy with Einstein (Madejski, Schwartz, 1988), } 2.08 \sim 2.24 \mu \text{Jy with EXOSAT (Sambruna et al. 1994), } 0.44 \sim 0.9 \mu \text{Jy with ROSAT (Comastri et al. 1995; Urry et al. 1996), and } 0.76^{+0.03}_{-0.06} \mu \text{Jy with ASCA in 1994 (paper I), all estimated at 1 keV.}\]

3. Discussion

The BL Lacertae object OJ 287 was observed twice in 1997 with ASCA, while the source was getting optically fainter after the optical outburst in 1994. The X-ray spectra obtained with the two sets of focal-plane instruments on board ASCA have been consistently described with a single power-law model modified with the Galactic absorption in both observations. The obtained source flux densities at 1 keV are lower and the spectra are harder in comparison with the previous X-ray results. No significant evidence of short-time variability was observed on time scales of hours.

Figure 3 shows the multi-frequency spectra of OJ 287 obtained in 1994 and 1997, including the present X-ray results. Radio and optical data in 1997 are presented by courtesy of Dr. Tapio Pursimo and the X-ray data in 1994 are taken from paper I. Compared with smooth extrapolations from the lower frequency continua, the X-ray spectra obtained with ASCA exhibit higher fluxes and flatter slopes in both observation results. Therefore the X-rays cannot be explained as an extension from the lower frequency SR component. Furthermore, the derived photon indices of \( \Gamma \sim 1.5 \), which are consistent with those of other well studied LBLs (Kubo et al. 1998), are much flatter than those of the SR component in well studied HBLs, typically \( \Gamma = 2.0 \sim 3.0 \) (Sambruna et al. 1996; Kubo et al. 1998). On the other hand, these photon indices are closer to those of IC X-rays observed from OVV quasars (e.g. Makino et al. 1989, 1991; Tashiro 1994; Kubo et al. 1998). These results suggest that the X-rays from OJ 287 observed with ASCA are dominated by the IC component, which is produced by electrons responsible for the radio to optical SR component.

Figure 4 shows the behavior of OJ 287 on the plane of X-ray photon index versus X-ray flux density at 1 keV.
(F_{1\text{keV}}), based on available measurements taken from paper I. Comparing the Einstein, EXOSAT, and ASCA measurements covering similar energy bands, the plot shows a constant photon index $\Gamma \sim 1.5$ in $F_{1\text{keV}} < 0.5 \mu\text{Jy}$, while the photon index increases with flux for $F_{1\text{keV}} > 1 \mu\text{Jy}$. Similar spectral behavior can be seen in some well-studied LBLs, such as S5 0716+714 (Giommi et al. 1999), ON 231 (Tagliaferri et al. 2000), and BL Lacertae (Tanihata et al. 2000), and is opposite to those of SR X-rays observed from HBLs which exhibit a harder X-ray spectrum for increasing intensity. This behavior of OJ 287 is interpreted that a decrease in the softer SR component unveils the harder IC components that is less variable. The systematic difference between the ROSAT data points and the ASCA-Einstein-EXOSAT ones can be explained that ROSAT, with its lower energy band, is more sensitive to the SR component than the other experiments. The convergence of figure 4 at photon index $\Gamma \sim 1.5$ and the stable light curve on short timescale strongly suggest that the X-rays observed in 1997 consist almost solely of the IC component.

Since the X-ray spectrum observed in the 1994 optical outburst is somewhat steeper ($\Gamma \sim 1.7$; paper I) than the limiting value of $\Gamma \sim 1.5$, it is thought to be a mixture of the SR and the IC components. In fact, a re-analysis of the 1994 data reveals that the spectrum above 2 keV is well described with a single power law model of $\Gamma = 1.54 \pm 0.04$ modified with the Galactic absorption ($\chi^2$/d.o.f. $= 209.6/232$). This photon index is consistent with that obtained on 1997 November 18, when the emission is almost purely of IC origin. However, using this parameter, the spectrum in the full energy range of ASCA (0.8 $\sim$ 10 keV and 0.6 $\sim$ 7.0 keV for the GIS and SIS, respectively) shows a soft excess below 2 keV ($\chi^2$/d.o.f. $= 540.0/369$). Thus, the 1994 spectrum is examined against a double power-law model modified with the Galactic absorption. One power-law represents the IC component, with photon index fixed at the best fit value of 1.51 in November 1997, and normalization also fixed at the value determined by the single power law fit above 2 keV. The other power-law represents the SR component, whose spectral parameters are left free. This model has given an acceptable fit ($\chi^2$/d.o.f. $= 368.1/368$) to the 1994 ASCA spectra, yielding the parameters given in table 2. In addition, the estimated photon index ($\Gamma \sim 2.6$) for the SR component is reasonable in comparison with the observed SR components in HBLs (Sambruna et al. 1996; Kubo et al. 1998). Figure 5 shows the SR and IC components obtained in this way, together with the multi-frequency spectrum observed in 1994. When extrapolated to lower frequencies, the SR component smoothly connects to the observed lower frequency SR continua.

In conclusion, as suggested by Idesawa et al. (paper I), the X-ray spectrum of OJ 287 is explained as a composite between the SR and the IC components. The present X-ray emission observed in 1997 is naturally attributed almost
entirely to the IC emission, while the 1994 spectrum is partly contributed by the SR component. These results give a support to the unified scheme of blazars, in which their multi frequency spectra are decomposed into SR and IC components, which compete in the X-ray band for LBLs.

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Table 1. Summary of power-law fits to the X-ray spectra of OJ 287 obtained with ASCA in 1997.

| Instrument | Photon index | $F_{1\text{keV}}$ * | $\chi^2$/d.o.f. | Photon index | $F_{1\text{keV}}$ * | $\chi^2$/d.o.f. |
|------------|--------------|---------------------|-----------------|--------------|---------------------|-----------------|
| SIS        | 1.58 ± 0.10  | 0.216 ± 0.014       | 34.3/47         | 1.44 ± 0.11  | 0.250 ± 0.017       | 31.1/68         |
| GIS        | 1.56 ± 0.21  | 0.211 ± 0.035       | 7.6/40          | 1.61 ± 0.17  | 0.265 ± 0.032       | 13.9/50         |
| SIS+GIS    | 1.57 ± 0.09  | 0.215 ± 0.013       | 42.0/89         | 1.51 ± 0.09  | 0.252 ± 0.015       | 47.4/120        |

* Flux density at 1 keV in unit of $\mu$Jy ($=10^{-32}$ W m$^{-2}$ Hz$^{-1}$)

Table 2. Spectral Parameters of the IC and SR components with ASCA in the 1994 outburst.

|                   | Photon Index | $F_{1\text{keV}}$ * |
|-------------------|--------------|---------------------|
| IC component      | 1.51 (Fixed) | 0.59 ± 0.02 †       |
| SR component      | 2.62 ± 0.26  | 0.11 ± 0.02         |

* Flux density at 1 keV in unit of $\mu$Jy ($=10^{-32}$ W m$^{-2}$ Hz$^{-1}$).

† Determined from the single power law fit above 2 keV with photon index of 1.51.
Figure Captions

Fig. 1. Summed SIS+GIS light curves for OJ 287 obtained in April (left) and November (right) in 1997. In each figure, upper panel shows the light curve in 2–10 keV and lower panel that in 0.5–2 keV. Each data point is binned into 96 min corresponding to the orbital period of the ASCA spacecraft.

Fig. 2. Background subtracted X-ray spectra of OJ 287 shown without removing the instrumental response, observed in April (left panel) and November (right panel) in 1997. Data from the two SIS detectors were summed into one spectrum and those from the two GIS detectors were summed into the other spectrum. Histograms show the power-law with Galactic absorption which best describes the GIS and SIS spectra simultaneously.

Fig. 3. Multi-frequency spectra of OJ 287 obtained simultaneously with the ASCA observations in 1994 and 1997.

Fig. 4. Relations between the X-ray photon index and the X-ray flux density at 1 keV from the available observations. The Einstein data are taken from Madejski, Schwartz (1988), EXOSAT data from Sambruna et al. (1994), ROSAT data from Urry et al. (1996), and ASCA data in 1994 from Idesawa et al. (1997). We adopted the averaged flux density for the Einstein data.

Fig. 5. The SR component and IC Component determined from the ASCA spectrum in 1994, together with the radio and optical data in 1994 (Paper I).
Multi wavelength spectra of OJ287

$\nu F_\nu$ (Jy Hz)

$\nu$ (Hz)

- OJ-94 project ’94 Nov
- ’97 Apr Nov & Dec
- Metsahovi et al
- Michigan et al
- ’94 Nov
- EGRET
- ASCA ’94 Nov
- Idesawa et al
- ’97 November
- ’97 April
