THE HARDEST X-RAY SOURCE IN THE ASCA LARGE SKY SURVEY: DISCOVERY OF A NEW TYPE 2 SEYFERT

MASAAKI SAKANO,1 KATSUJI KoyAMA,2 Такеші Tsuru,2 и HISAMitsu AwAKI2
Department of Physics, Kyoto University, Kyoto 606-8502 Japan; sakano, koyama, tsuru, awaki@cr.scphys.kyoto-u.ac.jp

YOSHIHIRO Ueda and TADAYUKI TAKAHASHI
Institute of Space and Astronautical Science, Kanagawa 229-8510 Japan; ueda@astro.isas.ac.jp, takahashi@astro.isas.ac.jp

MasaYuki AkiyAMa1 and KOUI Ohta
Department of Astronomy, Kyoto University, Kyoto 606-8502 Japan; akiyama, ohta@kusastro.kyoto-u.ac.jp

AND

TOru YaMADA
Astronomical Institute, Tohoku University, Sendai 980-8578 Japan; yamada@astr.tohoku.ac.jp

Received 1997 December 15; accepted 1998 April 22

ABSTRACT

We present results of the ASCA deep-exposure observations of the hardest X-ray source discovered in the ASCA Large Sky Survey (LSS) project, designated as AX J131501 + 3141. We extract its accurate X-ray spectrum, taking into account the contamination from a nearby soft source (AX J131502 + 3142) separated from it by only 1'. AX J131501 + 3141 exhibits a large absorption of $N_H = 6.4^{+2.3}_{-1.0} \times 10^{22}$ H cm$^{-2}$, with a photon index $\Gamma = 1.5^{+0.7}_{-0.3}$. The 2–10 keV flux was about $5 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$, and was time variable by a factor of 30% in 0.5 yr. From the highly absorbed X-ray spectrum and the time variability, as well as the results of the optical follow-up observations, we conclude that AX J131501 + 3141 is a type 2 Seyfert galaxy. Discovery of such a low-flux and highly absorbed X-ray source could have a significant impact on our understanding of the origin of the cosmic X-ray background.

Subject headings: diffuse radiation — galaxies: active — galaxies: individual (AX J131501 + 3141) —

1. INTRODUCTION

Since the discovery of the cosmic X-ray background (CXB) more than 30 yr ago (Giacconi et al. 1962), its origin has been a puzzle. With ROSAT, ~70% of the CXB below 2 keV has been resolved into point sources, more than 60% of which are type 1 active galactic nuclei (AGNs) (Vikhlinin et al. 1995; Hasinger 1996; McHardy et al. 1998; Hasinger et al. 1998). The source of the CXB above the 2 keV band, however, is less clear, owing to the absence of an imaging instrument in this energy band. One problem in the hard X-ray band, often referred as the spectral paradox (e.g., Fabian & Barcons 1992), is that the X-ray spectrum of the CXB in the 2–10 keV band is harder than that of a typical type 1 AGN, which is presumably the main contributor to the CXB below 2 keV. The 2–10 keV X-ray spectrum of type 1 Seyfert galaxies (most of the bright AGNs) are approximated by a power law with a mean photon index of 1.7 (Mushotzky, Done, & Pounds 1993), which is significantly steeper than that of the 2–10 keV CXB of about 1.4 (Gendreau et al. 1995). This fact implies that the origin of the CXB above 2 keV differs, at least in part, from that below 2 keV. In addition, 20% of the total energy of the CXB is contained in the 2–10 keV band, whereas only a few percent of the CXB is below 2 keV (see reviews by Fabian & Barcons 1992; Hasinger 1996). Thus, the 2–10 keV band is an essential energy range for solving the origin of the CXB.

ASCA is the first satellite with the capacity for hard X-ray (up to 10 keV) imaging and spectroscopy; hence, is presently the best satellite for investigating the CXB in the 2–10 keV band. In the ASCA Large Sky Survey project (LSS; Inoue et al. 1996; Ueda et al. 1998a), a continuous field of 7 deg$^2$ near the north Galactic pole was surveyed with a sensitivity higher than any previous surveys in this energy band. Ueda et al. (1998a) resolved a significant fraction of the CXB, about 30% of the CXB, into discrete sources at a sensitivity limit of $F_X \sim 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ (2–10 keV).

The mean photon index in the 2–10 keV band for these resolved sources [$F_X = (1-4) \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ in 2–10 keV] was found to be $\Gamma = 1.5 \pm 0.2$. This result is consistent with the idea that the photon index approaches that of the CXB, $\Gamma \sim 1.4$, as the source flux decreases. However, because of limited photon statistics, the spectral information on the resolved sources was too poor to address the nature of individual X-ray sources.

The hardest source in the LSS (hereafter referred to as the LSS hardest source) was found to show a photon index of $\Gamma \sim -0.2$, with no correction for absorption (Ueda 1996). However, it is unclear whether the apparent hard spectrum is due to a large absorption or to the flatness of the intrinsic spectrum. The LSS hardest source, which was found in an unbiased survey, would provide us with a good opportunity to investigate the nature of faint and hard sources that could contribute significantly to the CXB above 2 keV.

Therefore, we have performed follow-up ASCA and optical observations on the LSS hardest source. This paper reports the results of the ASCA deep-exposure observations, while results of the optical observations are given by Akiyama et al. (1998).

2. OBSERVATIONS AND DATA REDUCTIONS

We have made two follow-up ASCA observations of the LSS hardest source, on 1995 December 23–24 for approx-
imately 51,000 s and on 1996 June 6–8 for approximately 49,000 s. *ASCA* has four X-ray telescopes (XRT) with focal plane detectors of two Solid State Imaging Spectrometers (SIS0 and SIS1) and two Gas Imaging Spectrometers (GIS2 and GIS3). Details of these instruments are found in Serlemitsos et al. (1995), Burke et al. (1991, 1994), Ohashi et al. (1996), and Makishima et al. (1996), while a general description of *ASCA* can be found in Tanaka, Inoue, & Holt (1994). The observation modes were 1 CCD FAINT mode and PH nominal mode for the SISs and GISs, respectively. Data reduction and cleaning were made with the standard method (Day et al. 1995).

3. RESULTS AND ANALYSIS

3.1. X-Ray Images

The LSS hardest source was detected in both the observations. Figure 1 shows the SIS image obtained from the second observation in the soft (0.5–2 keV) (panel a) and hard (2–10 keV) (panel b) bands. The images show the sums of data from SIS0 and SIS1, smoothed with a Gaussian of $\sigma = 20$ pixels (0'54). One pointlike source is clearly seen in the 2–10 keV band image, which corresponds to the LSS hardest source. On the other hand, in the 0.5–2 keV band image we detected another pointlike source, the position of which shifts by about 1' from the peak found in the 2–10 keV band image, but we found no significant emission at the position of the LSS hardest source. The relative accuracy of the peak position of *ASCA* mainly depends on photon statistics. The photon counts of the sources were 120 counts and 380 counts in the 0.5–2 keV and 2–10 keV bands, respectively, the relative accuracy estimated to be $\sim 15'$. Hence, we conclude that the peak position in the 0.5–2 keV band corresponds to another new soft X-ray source (hereafter the soft source) that was not found in the LSS because of the lack of photon statistics. Both of the sources are marked with crosses in Figures 1a and 1b.

The nominal error of 1' for the absolute position of *ASCA* is mainly attributable to a misalignment of the attitude sensors on the satellite base plate, coupled with a mismatch of the thermal expansion coefficient (Ueda et al. 1998b). We restored this temperature-dependent error using the on-board housekeeping data, according to the method described in Ueda et al. (1998b). Finally, the peak positions for the soft and LSS hardest sources are determined to be $13^h15^m18^s, +31^d42'20''$ and $13^h15^m09^s, +31^d41'28''$, respectively, in the 2000 equinox, with error circles of 0.5 radii (90% confidence level). Accordingly, they are designated as AX J131502 + 3142 and AX J131501 + 3141.

3.2. Spectra Determined by Image Analysis

Since the half-power diameter of the *ASCA* point spread function (PSF) is about 3', it is difficult to take individual spectra of these two sources separated by only 1'. Hence, we extracted the energy spectra by analyzing images using the method described in Uno (1997). We made projected profiles of six different energy bands in the region illustrated in Figures 1a and 1b (dashed lines). Each energy band was selected to contain reasonable counts, at least 100, for the profile-fitting analysis described below. We only used the data of SIS0 and SIS1 to construct the combined images, because the angular resolution of the SISs is better than that of the GISs. The projected axis was selected along a constant right ascension line, which gives roughly the largest separation angle between the two sources. The profiles in the 0.5–2 keV and 2–10 keV bands are shown separately in Figure 1c. We fitted these profiles with a model consisting of a background and two projected PSFs. The PSFs of XRTs were constructed by a ray-tracing program (Kunieda et al. 1995). The systematic error in the

![Figure 1](image-url)

**Fig. 1.**—(a)–(b) SIS0 + SIS1 image contours in the second observation (1996 June). Coordinates are in J2000. Images are smoothed with a Gaussian of $\sigma = 20$ pixels (0'54). The contour levels are linearly spaced by ten lines from (a) 0 to $2.0 \times 10^{-3}$ c s$^{-1}$ per 16 pixels for the 0.5–2 keV band image and (b) 0 to $5.2 \times 10^{-3}$ c s$^{-1}$ per 16 pixels for the 2–10 keV band image. Peak positions corresponding to AX J131502 + 3142 and AX J131501 + 3141 are marked with crosses. (c) Projected profiles of the 0.5–2 keV and 2–10 keV bands in the region represented with dashed lines. Open circles and crosses correspond to the 0.5–2 keV and the 2–10 keV band data, respectively.
shapes of the PSFs is about 10% (Kunieda et al. 1995), which is much smaller than the statistical error. For the background, we used a model consisting of the CXB and the non-X-ray background (NXB). The CXB was produced by the ray-tracing program, and the NXB was modeled from the night Earth data (Ueda 1996). In the fitting, we fixed the positions, but allowed the fluxes of the two sources to vary. The background level was also varied. The best-fit fluxes of the two sources in the different energy bands give the energy spectra.

Using the energy spectra derived from the image fitting, we examined whether the spectral shapes were different in the two observations, and found probable variability in the total flux for AX J131501+3141, but no significant change in the spectral shapes for both the sources. Therefore, to increase statistics, we summed the data of the two observations for the spectral analysis, as shown in Figure 2. The spectra of both AX J131501+3141 and AX J131502+3142 were nicely fitted with a power law with absorption. The best-fit models and parameters are given in Figure 2 and Table 1 (methods A and B), respectively. Details of the analysis of the time variability are given in § 3.4.

3.3. The Mixed SIS/GIS Spectrum

To confirm the above results and tighten constraints on the spectra of the two sources, we examined the spectra by an independent method. First, we accumulated SIS0 + SIS1 spectra in a 3' radius circle centered at the peak of AX J131501+3141 for the summed data of the two observations. Since this spectrum inevitably contains photons from both AX J131502+3142 and AX J131501+3141, separated by only 1', we refer the spectrum as the "mixed SIS spectrum." We subtracted the background taken from the region of the opposite corner in the same SIS chip after correction for its position dependence in the detector plane (Ueda 1996). We constructed an auxiliary response function (ARF) at the position of AX J131501+3141. The ARF at the position of AX J131502+3142 differs by only 4%, which is negligible in the present analysis.

Since we already found two power-law sources in the image-fitted spectra, we fitted the mixed SIS spectrum with a model consisting of two power laws with independent absorptions (two-power-law model), each of which represents AX J131502+3142 and AX J131501+3141. In the fitting, the power-law indices, normalizations, and column densities for both the components are allowed to be free parameters. The fitting result was found to be acceptable with the best-fit model and parameters given in Figure 3 and Table 1 (method C). We confirmed that the results obtained here are consistent with those obtained from the image-fitted spectra. Note that the spectral parameters for AX J131501+3141 ($\Gamma = 2.3_{-1.3}^{+1.3}$, $N_H = 7.9_{-3.4}^{+5.3} \times 10^{22}$ H cm$^{-2}$) are more tightly constrained, while no further constraint is given to AX J131502+3142.

Since the GISs have a higher efficiency in the high-energy band than SISs, further constraints on the spectrum of AX J131501+3141 should be given by the GIS data. Thus, we constructed the GIS2 + GIS3 spectra from the summed image of the two observations within a 3' radius centered at the peak of AX J131501+3141. The background spectra

![Image](image_url)

**TABLE 1**

| METHOD*  | Photon Index | $N_H$ (10$^{22}$ H cm$^{-2}$) | Photon Index | $N_H$ (10$^{22}$ H cm$^{-2}$) | $\chi^2$/dof |
|----------|--------------|-------------------------------|--------------|-------------------------------|-------------|
| A ..........| 3.8$^{+0.6}_{-0.6}$ | 0.7$^{+2.4}_{-2.4}$ | ... | ... | 2.5/3 |
| B ..........| ... | ... | 2.8$^{+2.7}_{-2.7}$ | 11$^{+4.7}_{-4.7}$ | 2.6/3 |
| C ..........| >1.3 | 1.7$^{+0.6}_{-0.6}$ | 2.3$^{+1.6}_{-1.6}$ | 7.9$^{+3.3}_{-3.3}$ | 4.3/4 |
| D ..........| >-0.9 | 1.5$^{+0.6}_{-0.6}$ | 1.5$^{+0.6}_{-0.6}$ | 6.4$^{+2.3}_{-2.3}$ | 22.5/16 |

* Description of the methods: (A) SIS0 + SIS1 spectrum for the soft source AX J131502+3142, made with image fitting. An absorbed power law with all free parameters is used. (B) Same as model A, but for the hard source AX J131501+3141. (C) Mixed SIS Spectrum fitted with a two-component power-law model with absorption. (D) Same as model C, but for a combined fitting with SIS and GIS.
Figure 3.—Mixed SIS spectrum, with the best fit of the two–power-law model (method C).

were constructed from a 4′–6′ radius annular region centered at the source. The background-subtracted spectrum is given in Figure 4a (the mixed GIS spectrum). Finally, to make the tightest constraints on the spectra, we fitted the mixed GIS spectrum and the mixed SIS spectrum simultaneously with a two–power-law model. The fitting was acceptable within a 90% confidence level ($\chi^2$/dof = 22.5/16). The best-fit parameters for the soft source AX J131502 + 3142 and the hard source AX J131501 + 3141 are $\Gamma_{\text{soft}} > -0.9$, $N_{\text{H,soft}} = 1.5 \pm 0.3 \times 10^{22}$ H cm$^{-2}$, and $\Gamma_{\text{hard}} = 1.5 \pm 0.6$, $N_{\text{H,hard}} = 6.4 \pm 2.3 \times 10^{22}$ H cm$^{-2}$, respectively. The best-fit models and parameters are given in Figure 4a and in Table 1 (method D). Figure 4b shows two-parameter error contours for the photon index and the hydrogen column density of AX J131501 + 3141, obtained by simultaneous fitting.

3.4. Time Variability

Since the spectral shapes of the two observations show no significant difference (see § 3.2), we fixed the best-fit model obtained with method D for both SIS and GIS spectra, and separately fitted the spectrum in each observation, allowing only the normalization to vary. The best-fit fluxes are given in Table 2. While the flux of AX J131502 + 3142 did not change significantly, that of AX J131501 + 3141 increased by 29% $\pm$ 17%, with a 90% statistical error, in 0.5 yr from the first to the second observation.

4. DISCUSSION

We extracted the accurate spectrum of the LSS hardest source, AX J131501 + 3141, taking into account contamination from the nearby soft source, AX J131502 + 3142, from which no significant X-ray emission was found in the LSS (Ueda 1996). We found that AX J131501 + 3141 exhibits a large absorption of $N_{\text{H}} = (6 \pm 2) \times 10^{22}$ H cm$^{-2}$, with a photon index $\Gamma = 1.5 \pm 0.6$. It showed a long-term time variability between two observations separated by 0.5 yr. While the photon index of AX J131501 + 3141 is consistent with the canonical value of type 1 AGNs (e.g., Mushotzky et al. 1993), its absorption column density is larger than that of a typical type 1 AGN by more than an order of magnitude, although a portion of type 1 AGNs, about 10% (Schartel et al. 1997), show a column density larger than $5 \times 10^{22}$ H cm$^{-2}$.

It is important that this source is selected in a fully unbiased manner. Hence, its X-ray properties should

| Source       | Instrument | Epoch 1       | Epoch 2       |
|--------------|------------|---------------|---------------|
| AX J131502 + 3142 (0.5–2 keV) | SIS        | 0.16 $\pm$ 0.08 | 0.23 $\pm$ 0.08 |
| AX J131501 + 3141 (2–10 keV) | SIS        | 5.1 $\pm$ 0.8  | 6.7 $\pm$ 0.8  |
| GIS          |            | 4.5 $\pm$ 0.7  | 5.7 $\pm$ 0.7  |
| SIS + GIS*   |            | 4.8 $\pm$ 0.5  | 6.2 $\pm$ 0.5  |

Note.—Unit of flux is $10^{-13}$ erg cm$^{-2}$ s$^{-1}$. Each error is 90% confidence.

* Mean flux of AX J131501 + 3141 about SIS and GIS.
provide a key to understanding the general nature of the missing hard X-ray populations that constitute the CXB above 2 keV. Two major possibilities have been proposed to account for the apparent hard spectrum of the CXB: one is to introduce large absorptions of sources (e.g., Awaki 1991), the other is to consider populations of sources with intrinsically flat spectra (e.g., Morisawa et al. 1990; Di Matteo & Fabian 1997). Our results for the LSS hardest source strongly suggest that highly absorbed sources play an important role in the origin of the hard X-ray background.

The large absorption of $6 \times 10^{22}$ H cm$^{-2}$, the photon index of $\Gamma \sim 1.5$, and the time variability are common properties seen in type 2 Seyfert galaxies. In fact, systematic studies of type 2 Seyfert galaxies by Awaki et al. (1991) and Ueno (1996) revealed that they commonly show large absorptions of $\sim 10^{23}$ H cm$^{-2}$ and photon indices of 1.5–1.7. Akiyama et al. (1998) found one bright optical galaxy with $B = 17.25$ mag near the center of the X-ray error circle of 0.5 radius in the optical follow-up observations. No other optical source with flux larger than $B = 22.4$ mag is found in the error circle. Akiyama et al. (1998) performed spectroscopic observations of the bright galaxy and found that ratios of emission lines are similar to those found in type 2 Seyfert galaxies. The redshift of this galaxy was determined to be 0.07. From the redshift, the observed flux in the 2–10 keV band, $5 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$, can be converted to the absorption-corrected luminosity of $L_X \sim 2 \times 10^{43}$ ergs s$^{-1}$. This luminosity is consistent with those of Seyfert galaxies. Thus, we identify the source AX J131501+3141 found in the unbiased X-ray survey as a type 2 Seyfert galaxy. Using the log $N$–log $S$ relation from Hasinger et al. (1998), we estimate that the chance coincidence between AX J131501+3141 and AX J131502+3142 is ~3%. However, these two sources probably have no physical correlation, because AX J131502+3142 is likely to be a QSO that is more distant than the new type 2 Seyfert AX J131501+3141.

Awaki (1991), Madau, Ghisellini, & Fabian (1994), and Comastri et al. (1995) predicted that the combination of type 1 and type 2 AGNs could reproduce the CXB spectrum, based on a unified AGN scheme (e.g., Antonucci 1993). In this scheme, type 1 and type 2 AGNs are essentially the same objects observed from different viewing angles. These type 2 AGNs, which exhibit apparently fainter and harder X-ray spectra than type 1 AGNs, should become detectable as the detector sensitivity increases. Although we have examined only one sample from the LSS at this moment, the result is encouraging not only for the unified AGN scheme, but also for solving the origin of the CXB.

The authors express their thanks to all the members of the ASCA team whose efforts made these observations and data analysis possible. We thank the referee, G. Hasinger, for his useful advice. We are grateful to H. Inoue for his valuable comments. M. S. thanks Y. Maeda for discussions. M. S. and M. A. acknowledge support from the Japan Society for the Promotion of Science for Young Scientists.

**REFERENCES**

Akiyama, M., et al. 1998, ApJ, 500, 173
Antonucci, R. 1993, ARA&A, 31, 473
Awaki, H. 1991, Ph.D. thesis, Nagoya Univ.
Awaki, H., Koyama, K., Inoue, H., & Halpern, J. P. 1991, PASI, 43, 195
Burke, B. E., Mountain, R. W., Daniels, P. J., & Dolat, V. S. 1994, IEEE Trans. Nuc. Sci., 41, 375
Burke, B. E., Mountain, R. W., Harrison, D. C., Bautz, M. W., Doty, J. P., Ricker, G. R., & Daniels, P. J. 1991, IEEE Trans., ED-38, 1069
Comastri, A., Setti, G., Zamorani, G., & Hasinger, G. 1995, A&A, 296, 1
Day, C., Arnaud, K., Ebisawa, K., Gottthelf, E., Ingham, J., Mukai, K., & White, N. 1995, The ABC Guide to ASCA Data Reduction (Greenbelt: NASA/Goddard Space Flight Center)
Di Matteo, T., & Fabian, A. C. 1997, MNRAS, 286, 393
Fabian, A. C., & Barcons, X. 1992, ARA&A, 30, 429
Gendreau, K. C., et al. 1995, PASJ, 47, L5
Giacconi, R., Gursky, H., Paolini, F. R., & Rossi, B. B. 1962, Phys. Rev. Lett., 9, 439
Hasinger, G. 1996, A&AS, 120, 607
Hasinger, G., Burg, R., Giacconi, R., Schmidt, M., Trümper, J., & Zamorani, G. 1998, A&A, 329, 482
Inoue, H., Kii, T., Ogasa, Y., Takahashi, T., & Ueda, Y. 1996, in Röntgenstrahlung from the Universe, ed. H. U. Zimmermann, J. Trümper, & H. Yorke (Garching bei München: Max-Planck-Institut für extraterrestrische Physik), 323
Kunieda, H., Furuzawa, A., Watanabe, M., & The ASCA XRT Team. 1995, ASCA News (NASA/Goddard Space Flight Center), 3, 3
Madau, P., Ghisellini, G., & Fabian, A. C. 1994, MNRAS, 270, L17
Makishima, K., et al. 1996, PASJ, 48, 171
McHardy, I. M., et al. 1998, MNRAS, 295, 641
Morisawa, K., Matsuoka, M., Takahara, F., & Piro, L. 1990, A&A, 236, 299
Mushotzky, R. F., Done, C., & Pounds, K. A. 1993, ARA&A, 31, 717
Ohashi, T., et al. 1996, PASJ, 48, 157
Schartel, N., Schmidt, M., Fink, H. H., Hasinger, G., & Trümper, J. 1997, A&A, 320, 696
Serlemitsos, P. J., et al. 1995, PASJ, 47, 105
Tanaka, Y., Inoue, H., & Holt, S. S. 1994, PASJ, 46, L37
Ueda, Y. 1996, Ph.D. thesis, Tokyo Univ.
Ueda, Y., et al. 1998a, Nature, 391, 866
---. 1998b, ASCA News (NASA/Goddard Space Flight Center), in press
Ueno, S. 1996, Ph.D. thesis, Kyoto Univ.
Uno, S. 1997, Ph.D. thesis, Gakusyuin Univ.
Vikhlinin, A., Forman, W., Jones, C., & Murray, S. 1995, ApJ, 451, 553