DETECTION OF IRON EMISSION LINES FROM THE GALAXY CLUSTER INCLUDING THE RADIO GALAXY 3C 220.1 AT z = 0.62

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ABSTRACT

We have detected an emission-line feature at 4 keV in the X-ray emission from a sky region including the distant radio galaxy 3C 220.1 (z = 0.62) obtained with ASCA. The line energy is 6.1–7.0 keV (90% confidence) in the rest frame of 3C 220.1. Within the present statistics, the observed spectra are consistent with two different models: a nonthermal model consisting of a power-law continuum plus a 6.4 keV iron emission line and a Raymond-Smith thin thermal emission model of kT ~ 6 keV with a metal abundance of ~0.5 solar. However, because of the large (~500 eV) equivalent width of the line, a significant fraction of the X-ray emission is likely to arise from the hot intracluster gas associated with the galaxy cluster that includes 3C 220.1. The spectral parameters of the thermal emission are consistent with the luminosity-temperature relation of nearby clusters.

Subject headings: dark matter — gravitational lensing — galaxies: clusters: individual (3C 220.1) — X-rays: galaxies

1. INTRODUCTION

Among a variety of attempts searching for clusters at high redshifts, X-ray observation directly illuminates the gravitational potential well because the X-ray–emitting hot plasma is considered to trace it. Moreover, X-ray emission lines from highly ionized ions, iron in particular, can be used to determine the redshift of the hot gas, and thereby its association with other objects can be investigated. Based on these ideas we have conducted an observation of the radio galaxy 3C 220.1 with ASCA.

The existence of a galaxy cluster that surrounds the radio galaxy 3C 220.1 (z = 0.62) was first suggested from the observations at Lick Observatory (Dickinson 1984). Around the radio galaxy in the Lick image, several quite red galaxies were found. Further observations were performed at Kitt Peak National Observatory, and the blue-band image revealed the presence of a giant luminous arc (Dickinson 1984). In 1995, much higher quality images were obtained with the Hubble Space Telescope (M. Dickinson 1998, private communication). A large arc (9° in radius and subtending ~70° around the radio galaxy) was clearly resolved.

The arc image of 3C 220.1 is regarded as a section of an Einstein ring caused by gravitational lensing. This offers a remarkable tool to constrain the cluster mass enclosed within it. The redshift of the arc was successfully determined with the Keck telescope to be zₐ = 1.49 (Dickinson 1998, private communication). Under an assumption of spherically symmetric geometry, the projected lensing mass within the arc radius, 9°, is Mₖen(<9°) = 3.8 × 10¹³ M☉. Here Ω₀ = 1, Λ = 0, and H₀ = 50 km s⁻¹ Mpc⁻¹ are adopted. The derived mass is appropriate for clusters of galaxies rather than a single galaxy.

A strong piece of evidence for the existence of a galaxy cluster around 3C 220.1 was obtained by X-ray observation with ROSAT observatory (Hardcastle, Lawrence, & Worrall 1998). The ROSAT HRI image revealed that the X-ray emission consists of a compact central component and an extended component that can be attributed to cluster emission. The ratio of the count rates of the compact to the extended components in the ROSAT HRI energy band is about 2.3.

In this paper we report the detection of an iron K emission line with ASCA and discuss the origin of the X-ray emission.

2. OBSERVATION AND RESULTS

2.1. Observation

We observed 3C 220.1 with the ASCA Gas Imaging Spectrometers (GIS) and Solid-State Imaging Spectrometers (SIS) for 40 ks on 1998 April 11, during the AO6 period. The GIS was operated in the PH nominal mode, while the SIS was in the faint 1 CCD mode. The data were filtered by the standard ASCA data-screening procedure.

X-ray emission centered at 9°32′43″, +79°06′39″ (J2000.0) is detected. The peak position is about 0.2 off from the cataloged value of 3C 220.1 but is consistent with it within the uncertainty of ASCA attitude determinations (0.5 at 90% confidence). The source count rates are (6.6 ± 0.4) × 10⁻³ counts s⁻¹ in the 0.7–8 keV band for the GIS and (8.6 ± 0.5) × 10⁻³ counts s⁻¹ in the 0.5–8 keV band for the SIS within a circle of 3′ radius centered on the peak position, after background subtraction. In the GIS and SIS fields, there are several other bright sources in the vicinity of 3C 220.1. Most of them are not identified with known objects, except for one at 9°31′34″, +79°04′9″ (J2000.0), which is a radio-loud active galactic nucleus (AGN; see comments in Hardcastle et al. 1998).

2.2. Spectral Analysis

Since the angular separations between 3C 220.1 and the three nearby sources are 3′4–5′1, the contamination of 3C 220.1’s energy spectrum from these sources must be carefully treated. In order to check the contribution due to the nearby sources, we have accumulated the energy spectra in two different integration regions: (1) a circular region cen-
Fig. 1.—Spectral fits of ASCA SIS (0 + 1) and GIS (2 + 3) spectra with (upper panel) a power-law model and (lower panel) a power-law plus a Gaussian model. The crosses denote the observed spectra, and the step functions show the best-fit model function convolved with the X-ray telescope and the detector response functions. In the lower panel, the Gaussian component (dotted line) is shown.

Iron emission from galaxy cluster at $z = 0.62$ was observed. Spectral fits of ASCA SIS (0 + 1) and GIS (2 + 3) spectra were performed. The crosses denote the observed spectra, and the step functions show the best-fit model function convolved with the X-ray telescope and the detector response functions. In the lower panel, the Gaussian component is shown.

3C220.1 ASCA spectra

For both power-law and Raymond-Smith models, the resultant model parameters for the different extraction regions are consistent with each other within the statistical errors.

Sources were excluded from the analysis. Sources were excluded from the analysis. The radii of the excluded regions are proportional to the intensities of the nearby sources. We then evaluated these two spectra by model fittings. For both power-law and Raymond-Smith models, the resultant model parameters for the different extraction regions are consistent with each other within the statistical errors.
errors. In what follows, we show the results for case 1 because at present only the azimuthally averaged response function is available for the X-ray telescope; thus case 2 may involve some systematic errors.

The PHA (pulse height analysis) channels of the spectra were first converted to PI (pulse invariant) channels and the spectra of the two telescopes of the same system, i.e., SIS-0 and 1 and GIS-2 and 3, respectively, were added together. Some of the PI bins are combined together so that the number of counts in any combined PI bin is greater than 30.

We subtracted background spectra estimated in two different ways and compared the results in order to estimate systematic errors. In the first case (case A), the spectrum was estimated from the present observation. For the GIS background, we accumulated events from annular image regions whose centers are at the optical axes of the telescopes. The outer and inner radii are equal to the maximum and minimum angular distances, respectively, of the target spectrum region from the optical axis. We excluded regions 4' from the target and the contaminating sources, while for the SIS background, image regions were selected outside 4' from the target and 3' from the contaminating sources. In the second case (case B), the standard background spectrum that was obtained through blank sky-field observations during the ASCA PV phase was used. The background was derived from the same detector region as the target on the SIS/GIS detector coordinates. The systematic errors of background originate from spatial fluctuations of the cosmic X-ray background, the detector-position dependence of cosmic X-ray background and non-X-ray background, and temporal variation of non-X-ray background. Their contributions to the above two backgrounds are different. However, the spectral fits using the different backgrounds provided consistent results within the statistical errors. Thus the systematic errors are smaller than Poisson statistical errors. Since the statistical errors of parameters using case B are smaller than those using case A by 30–50%, we will show the results obtained with case B hereafter.

We fitted the GIS and SIS spectra simultaneously with model spectra. First we tried a simple single-component model: a single–power-law model with neutral absorption with a column density fixed at the Galactic value, \( N_H = 1.93 \times 10^{20} \) cm\(^{-2}\). The absorption is fixed at this value throughout this paper. The fits are acceptable with a best-fit power-law photon index of 1.9 (1.7–2.0, 90% error); however, the fit leaves two excess data points at around 4 keV for both the SIS and GIS spectra (Fig. 1).

The deviations of the data from the model in the 3.2–4.3 keV band are only 0.2–2.1 σ. However, the probability that we should observe such deviations in any corresponding consecutive energy bins of two different detectors is encouragingly low, \( \sim 0.5\% \). Thus we added a narrow Gaussian emission line to the model with the Gaussian center energy left free. The result is shown in Table 1 and Figure 1. In comparison to the single–power-law model fit, the fit improves from a \( \chi^2 \) value of 33.9 for 34 degrees of freedom (dof) to 26.5 for 32 dof. The improvement is significant by the F-test at the 98.1% confidence level. Thus we conclude that the emission-line feature is significant at the 98.1% confidence level.

The best-fit Gaussian center energy is 3.9 keV in our frame with a 90% error range of 3.8–4.2 keV. The most likely origin of this line feature is a redshifted iron emission line. If we assume low-ionization iron emission lines at 6.4 keV, the redshift is estimated to be 0.63 (0.53–0.69, 90% error), while if we assume 6.7 keV lines from helium-like iron, the redshift is 0.71 (0.61–0.76). Therefore the redshift of the radio galaxy \( z = 0.62 \) is within the error range in either case. Thus, it is most likely that the emission is originating from 3C 220.1 or the cluster surrounding it. Then the central energy is estimated to be 6.3 (6.1–7.0) keV in the rest frame. It can be interpreted either as a 6.4 keV low-ionization iron emission line, which may be associated with an AGN, 6.7/6.9 keV lines from highly ionized iron, which may be attributed to cluster hot gas, or a combination of these two. We are not able to distinguish these emission lines under the current limited statistics and detector resolutions.

Thus, we next performed fits with models corresponding to the above two extreme cases: a power-law model plus a

### TABLE 1

**RESULTS OF SPECTRAL FITS**

| Parameter | Value (error*) |
|-----------|---------------|
| Photon index | 1.9 (1.7–2.0) |
| \( \chi^2/dof \) | 33.9/34 |

**Power-Law Model**

| Parameter | Value (error*) |
|-----------|---------------|
| Photon index | 1.9 (1.8–2.1) |
| Gaussian center energy (keV) | 3.9 (3.8–4.2) |
| \( \chi^2/dof \) | 26.5/32 |

**Power-Law Plus Gaussian Model**

\( \chi^2(Stark et al. 1992) \). The absorption is fixed at the Galactic value, \( N_H = 1.93 \times 10^{20} \) cm\(^{-2}\). The absorption is fixed at this value throughout this paper. The fits are acceptable with a best-fit power-law photon index of 1.9 (1.7–2.0, 90% error); however, the fit leaves two excess data points at around 4 keV for both the SIS and GIS spectra (Fig. 1).

The deviations of the data from the model in the 3.2–4.3 keV band are only 0.2–2.1 σ. However, the probability that we should observe such deviations in any corresponding consecutive energy bins of two different detectors is encouragingly low, \( \sim 0.5\% \). Thus we added a narrow Gaussian emission line to the model with the Gaussian center energy left free. The result is shown in Table 1 and Figure 1. In comparison to the single–power-law model fit, the fit improves from a \( \chi^2 \) value of 33.9 for 34 degrees of freedom (dof) to 26.5 for 32 dof. The improvement is significant by the F-test at the 98.1% confidence level. Thus we conclude that the emission-line feature is significant at the 98.1% confidence level.

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Thus, we next performed fits with models corresponding to the above two extreme cases: a power-law model plus a
Gaussian emission line with the line center energy fixed at 6.4 keV, and a Raymond-Smith model representing an optically thin thermal plasma emission. We fixed the redshift value at the position of the radio galaxy, 0.62. The results of these fits are shown in Figure 2 and Table 2, where the model parameters for the GIS and SIS spectrum are combined. Although both models are acceptable at the 90% confidence limit, the Raymond-Smith model gives a smaller reduced $\chi^2$ value. The luminosity in the 2–10 keV band is $1 \times 10^{45}$ ergs s$^{-1}$, assuming a distance of $z = 0.62$. 

Fig. 2.—Spectral fits of ASCA SIS (0 + 1) and GIS (2 + 3) spectra with (upper panel) a power-law plus 6.4 keV (rest-frame) Gaussian model and with (lower panel) a Raymond-Smith model. The redshift of the object is assumed to be 0.62. In the upper panel, the Gaussian component (dotted line) is shown.
For the nonthermal model consisting of a power law plus a 6.4 keV line, we obtained an equivalent width of ~500 (190–780) eV, while for the Raymond-Smith fit, we found a metal abundance of 0.54 (0.17–1.0) solar. In Figure 3 we have plotted the $\chi^2$ contours as a function of two of the Raymond-Smith model parameters: $kT$ and metal abundance.

3. DISCUSSION

We have detected an emission line at 3.9 keV (3.8–4.2 keV) in our rest frame, which corresponds to 6.1–7.0 keV at $z = 0.62$. Within the present statistics, the observed spectra are consistent with two different models, a nonthermal model that consists of a power-law continuum and a 6.4 keV emission line and a Raymond-Smith thermal model with temperature about 6 keV. In this section, we discuss the origin of the X-ray emission.

The radio source 3C 220.1 is classified as an FR II narrow emission line galaxy (NELG). Turner et al. (1997) investigated the narrow iron K line at 6.4 keV from type 2 AGNs systematically and reported that most of the NELGs show an equivalent width smaller than 200 eV and on average ~100 eV. Thus, for 3C 220.1, the derived equivalent width under a nonthermal model is a factor of 2–8 larger than the typical NELGs if one attributes all of the line intensity to the radio galaxy 3C 220.1. This indicates a large (>50%) fraction of the iron line is emitted from the other emission region, most likely the intracluster medium in the galaxy cluster.

The ROSAT HRI observations revealed that the X-ray emission consists of a compact component and an extended component, which is significantly extended more than 10'' in radius and carries about 60% of the HRI photons (Hardcastle et al. 1998). Since the two spectral models in our analysis are not distinguished within the statistics, any combination of the two models should also be statistically acceptable. If the compact component carries 40% of the photons in the ASCA energy band and contains an iron emission line of 100 eV equivalent width in its own spectrum, the equivalent width of the rest of the emission is expected to be 250–1200 eV. This value is appropriate for thin thermal emission of $kT \sim 6$ keV with a metal abundance of 0.2–1.6 solar.

If we consider about 60% of the total emission to arise from the cluster, the luminosity and the temperature obtained from the spectral fit are consistent with the luminosity-temperature relation for nearby clusters obtained by David et al. (1993) within the scatter of data points.

The masses of distant clusters determined from the gravitational arc (lens mass) and determined from the X-ray observations (X-ray mass) have been compared by several authors (e.g., Wu & Fang 1997). These results show that in general the X-ray mass is either consistent with or smaller than the lens mass. Under the assumption of hydrostatic equilibrium, isothermal and spherical distribution of the intracluster gas, and $\beta$-model surface brightness distribution, the X-ray mass projected within a radius $r$ is estimated as $M_{X\beta}(r) = (3kT/\beta G\bar{m})(\pi/2)[r^2/(r^2 + r_c^2)^{1/2}]$, where $k$ is the Boltzmann constant and $\bar{m}$ is the mean mass per plasma particle (Ota, Mitsuda, & Fukazawa 1998). Adopting the best-fit $\beta$-model parameters obtained from the ROSAT HRI observations ($\beta = 0.9$ and the core radius $r_c = 13''$), we find that the X-ray mass contained within the arc radius is equal to or smaller than the lens mass if the temperature of the X-ray emission is lower than 6.4 keV. The determined X-ray temperature of $5.6^{+1.3}_{-1.1}$ keV from the single Raymond-Smith model fits is consistent with this.

In conclusion, a large fraction of the iron line emission and the continuum emission associated with the line is likely to originate from the intracluster medium in the galaxy cluster around 3C 220.1. This is strong evidence for the existence of a cluster of galaxies including 3C 220.1.

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