Detection of Iron Emission Line from the Galaxy Cluster Including the Distant Radio Galaxy 3C220.1

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ABSTRACT

We detected an emission line feature at 4 keV in the X-ray spectrum of a sky region including the distant radio galaxy 3C220.1 ($z = 0.62$) obtained with ASCA. The line energy is 6.1 – 7.0 keV (90% confidence) in the rest frame of 3C220.1. Within the present statistics, the observed spectra are consistent with two different models: a non-thermal model consisting of a power-law continuum plus a 6.4 keV iron emission line, and a Raymond-Smith thin-thermal emission model of $kT \sim 6$ keV with a metal abundance of $\sim 0.5$ solar. However, the large ($\sim 500$ eV) equivalent width of the line indicates that a significant fraction of the X-ray emission is likely to arise from the hot intracluster gas associating the galaxy cluster including 3C220.1. The spectral parameters of the thermal emission are consistent with the luminosity-temperature relation of nearby clusters and the mass estimates from the giant luminous arc.

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, thereby its association with other objects can be investigated. Based on these ideas we have conducted an observation of the radio galaxy 3C220.1 with ASCA.

An existence of a galaxy cluster which surrounds the radio galaxy 3C220.1 ($z = 0.62$) was first suggested from the observations at Lick Observatory (Dickinson, 1984). Around the radio galaxy in the Lick image, the presence of 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 Hubble Space Telescope (Dickinson, 1998). A large arc (9 arc seconds in radius and subtending $\sim 70$ degrees around the radio galaxy) was clearly resolved.

The arc image of 3C220.1 is very symmetric and 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 using the Keck telescope to be $z_s = 1.49$ (Dickinson, 1998). Under an assumption of spherically symmetric geometry, the projected lensing mass within the arc radius, $9''$, is $M_{\text{lens}}(<9'') = 3.8 \times 10^{13} M_\odot$. Here $\Omega_0 = 1$, $\Lambda = 0$, and $H_0 = 50$ km sec$^{-1}$Mpc$^{-1}$ are
adopted. The derived mass is appropriate to clusters of galaxies rather than a single galaxy.

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 3C220.1 with the ASCA GIS and SIS for 40 ksec on 1998 April 11, in AO6 period. The GIS was operated in the PH nominal mode, while the SIS was in the Faint 1CCD mode. The data were filtered by the standard ASCA data screening procedure.

The X-ray emission centered at \((9^h32^m43^s, +79^\circ06'39'')_{J2000.0}\) is detected. The peak position is about 0.2 arcmin off from the cataloged value of 3C220.1, however is consistent with it within the uncertainty of ASCA attitude determinations (0.5 arcmin at 90% confidence). In the GIS and SIS fields, there are several other bright sources in the vicinity of 3C220.1. Most of them are not identified with known objects, except for one at \((9^h31^m34^s, +79^\circ04'9'')_{J2000.0}\) which is a radio-loud AGN (see comments in Hardcastle et al. 1998).

2.2 Spectral Analysis

Since the angular separations between 3C220.1 and three nearby sources are 3.4 to 5.1 arcmin, contamination of 3C220.1 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 centered on 3C220.1 with a radius of 3.0' and (2) the same circular region as (1) but excluding three circular areas centered on the nearby sources. The radii of the excluded regions are proportional to the intensity of the nearby sources. We then evaluated these two spectra by model-fittings. For both power-law model or Raymond-Smith model, the resultant model parameters are consistent with each other within the statistical 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.

Firstly we tried a single power-law model with a neutral absorption with a column density fixed at the Galactic value, \(N_H = 1.93 \times 10^{20}\text{cm}^{-2}\) (Stark et al. 1992). The absorption is fixed to this value throughout this paper. The fits are acceptable with a best-fit power-law photon index of 1.9\(^{+0.1}_{-0.2}\), 90% error), however, the fit leaves two excess data points at around 4 keV for the SIS and GIS spectra. If we add a narrow Gaussian emission line, the fit improves from the \(\chi^2\) value of 33.9 for 34 degrees of freedom to 26.4 for 31 degrees of freedom. The improvement is significant by the F-test at a 95% confidence limit.

The best-fit Gaussian central energy is 3.9 keV in our frame with the 90% error range of 3.8 – 4.2 keV. The most likely origin of this line feature is a red-shifted 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 irons, 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.

If we assume that the line emission is originating from an object at \(z = 0.62\), the central energy is estimated to be 6.3(6.1 – 7.0) keV in the rest frame. It can be interpreted either as 6.4 keV low-ionization iron emission line which may be associated with the AGN, 6.7/6.9 keV lines from highly ionized irons 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 the detector resolutions.

Thus next, we performed fits with models corresponding to the above two cases; power-law model plus a Gaussian with line center energy fixed at 6.4 keV and Raymond-Smith model representing an optically thin thermal plasma emission. In Figure [I] and Table [I], the results of the fits are shown, where the model parameters for the GIS and SIS spectrum are combined except for their normalization factors. Although both models are acceptable at the 90% confidence limit, the Raymond-Smith model gives a smaller reduced \( \chi^2 \) value.

| Model                | Parameter          | Value(error\textsuperscript{a}) |
|----------------------|--------------------|----------------------------------|
| Power-law plus Gaussian | Photon Index      | 1.9(1.8 – 2.1)                  |
|                      | Equivalent width[eV]\textsuperscript{b} | 480(190 – 780)                  |
|                      | \( L_X^{2-10} \) [erg/s]\textsuperscript{c} | 8.4 \times 10^{44}           |
|                      | \( \chi^2/d.o.f. \) | 26.7/32                         |
| Raymond-Smith        | \( kT \) [keV]    | 5.6(4.5 – 7.1)                  |
|                      | Abundance[Z\odot] | 0.54(0.17 – 1.0)                |
|                      | \( L_X^{2-10} \) [erg/s]\textsuperscript{c} | 8.4 \times 10^{44}           |
|                      | \( \chi^2/d.o.f. \) | 18.0/33                         |

The absorption column density is fixed at the Galactic value; \( N_H = 1.93 \times 10^{20} \text{cm}^{-2} \). \textsuperscript{a}The quoted errors correspond to a single parameter error at 90% confidence. \textsuperscript{b}A narrow line at 6.4 keV is assumed. \textsuperscript{c}Absorption corrected 2 – 10 keV luminosity assuming the distance of \( z = 0.62 \).

Figure 1: ASCA SIS(0+1) and GIS(2+3) spectra fitted with the power-law plus Gaussian model(left panel), and the Raymond-Smith model(right panel). 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.

3 DISCUSSION

We have detected an emission line at 4 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 non-thermal model which 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 3C220.1 is classified as an FRII 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 most of the NELG shows an equivalent width smaller than 200 eV and on average $\sim$ 100 eV. Thus for 3C220.1, the derived equivalent width under a non-thermal model is a factor of 2 to 8 larger than the typical NELGs if one attributes all of the line intensity to the radio galaxy 3C220.1. This indicates a large (> 80%) fraction of the iron line is emitted from the other emission region; most likely intracluster medium of the galaxy cluster.

The ROSAT HRI observations revealed that the X-ray emission consists of an extended ($\sim 10''$) component which carries about 60% of the HRI photons and a compact central component (Hardcastle et al. 1998). Since two spectral models in our analysis are not distinguished within the statics, any combinations of the two models should also be statistically acceptable. If the compact component carries 40% of photons in the ASCA energy band and contains an iron emission line of 100 eV equivalent width in its own spectrum, the equivalent width for the rest of the emission is expected to be 150 eV to 1100 eV. This value is appropriate for a thin thermal emission of $kT \sim 6$ keV with metal abundance of 0.2 to 1.3 solar.

If we consider about 60% of the total emission is arising 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 various 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 shows that in general the X-ray mass becomes either consistent with the lens mass or smaller. Adopting the $\beta$ model parameters obtained from the ROSAT HRI observations ($\beta = 0.9$ and the core radius, $r_c = 13''$), we obtain that the X-ray mass becomes equal 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 $5.6^{+1.5}_{-1.1}$ keV from the single Raymond-Smith model fits suggests this is the case.

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 3C220.1. This is a strong evidence for the existence of the cluster of galaxies including 3C220.1.

4 REFERENCES

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