DISCOVERY OF SOFT X-RAY ARC FROM THE SEYFERT 2 GALAXY NGC 4388 IN THE VIRGO CLUSTER

R. Iizuka, H. Kunieda, and Y. Maeda
Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan

Abstract

Recently, the very largely extended, ∼35 kpc, Hα emission was first detected from NGC 4388 with Subaru by Yoshida et al. (2002). We analyzed the archived Chandra data of NGC 4388 paying attention to the extended emission. We discovered soft X-ray arc-like structure (the X-ray arc). The X-ray arc is largely elongated from the galaxy to northeast (∼30 kpc). The position of the X-ray arc roughly coincides with that of Hα. The spectrum could be fitted with a thin thermal plasma model with a temperature of ∼1 keV and a density of ∼5×10^{-3} cm^{-3}. The X-ray arc is cooler and denser than the ICM of the Virgo cluster. Therefore, the X-ray arc is not the ICM. The probable origin of the X-ray arc is a heated gas stripped by the ram-pressure of the ICM. The Chandra image might take a picture at the moment that the galaxy’s gas is being supplied into the intracluster space.

1 Introduction

Extended emission-line regions in galaxies are usually associated with active galactic nuclei. It is widely recognized that most of them are photoionized by the nuclear power-law ionizing continuum.

NGC 4388 is one of the nearby Seyfert 2 galaxies. NGC 4388 is also a member galaxy of Virgo cluster, located within 1° of the two cD galaxies, M84 and M86 (Fig. 1). Although the recession velocity of NGC 4388 (∼2540 km s^{-1}) is substantially higher than the cluster mean velocity of 1100 km s^{-1}. Its distance estimated from the Tully-Fisher relation (16.7 Mpc) is close to that of the cluster center.

Recently, Yoshida et al. (2002) found a very extended emission-line region (VEELR) around NGC 4388 in deep, narrow-band images made with the Subaru Telescope (Fig. 5). The extension of the emission-line region is extending up to 35 kpc away from the nucleus. This region consists of many faint gas clouds, or filaments, and extends northeastward from the galaxy in a whole. Yoshida et al. (2002) suggest that the excitation mechanism of the inner (r<12 kpc) region may be due to nuclear ionizing radiation, while the outer (r>12 kpc) is enigmatic.

2 Data analysis and Results

NGC 4388 was observed with ACIS-S for 20ks on 2001 Jun 8. We analyzed the Chandra data of NGC 4388 paying attention to the extended region. We hence focused on the data analysis of ACIS-S3 where the nucleus is covered (8′ × 8′). The data reduction with the standard criteria was applied.

Fig. 6 shows the adoptively smoothed image in soft (0.5-2.0 keV) and hard (2.0-8.0 keV) band. Fig. 7 shows the X-ray contours overlaid on the Hα image. In the hard band, a strong
point-like emission appears at the center of the galaxy (Fig. 6 right). The position of the hard source coincides with that of the nucleus (Fig. 7). A spectrum analysis of this hard source confirmed an absorbed spectrum (Fig. 2), so that NGC 4388 harbors a Seyfert 2 nucleus. In the soft band, several extended structures were detected (Fig. 6 left). The brightest structure is located around the nucleus and is well overlaid with the optical disk of the galaxy. In addition, two extended regions (1 and 2) appeared in the halo. The region 1 showed an arc-like structure elongated to the northeast direction from the galaxy with the length of \( \sim 6 \) arcmin, which is corresponding to \( \sim 30 \) kpc. The region 2 is more compact but more brighter than the region 1. Its length is \( \sim 1 \) arcmin (5 kpc). It is notable results that the region 1 is elongated to the different direction from the VEELR in optical, but that the region 2 is coincided with the \( \text{H} \alpha \) (Fig. 7).

Spectra of these two regions could be fitted by thin thermal plasma model (Fig. 3). Due to the limited statistics, abundance(0.16) was fixed to the upper limit of the Seyfert nucleus (Fig. 2). The absorption column was fixed at the Galactic number of \( 2.55 \times 10^{20} \) cm\(^{-2} \) (Murphy et al. 1996). The best-fit parameters are shown in Table 1. The temperature of the X-ray arc is \( < 1 \) keV which is lower than the Virgo ICM (\( \sim 2 \) keV). The density is \( > 10^{-3} \) cm\(^{-3} \) which is higher (\( \sim 10^{-4} \) cm\(^{-3} \)).

### Table 1: Spectra fitting parameter

<table>
<thead>
<tr>
<th>Region</th>
<th>Temperature [keV]</th>
<th>Luminosity [erg s(^{-1})]</th>
<th>Volume [kpc(^3)]</th>
<th>density [cm(^{-3})]</th>
<th>Mass [M(_{\odot})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3 (0.2-0.8)</td>
<td>( 5 \times 10^{39} )</td>
<td>( \sim 250 )</td>
<td>( 4 \times 10^{-3} )</td>
<td>( 3 \times 10^7 )</td>
</tr>
<tr>
<td>2</td>
<td>1 (0.8-2)</td>
<td>( 2 \times 10^{39} )</td>
<td>( \sim 35 )</td>
<td>( 7 \times 10^{-3} )</td>
<td>( 4 \times 10^7 )</td>
</tr>
</tbody>
</table>

### 3 Origin of the X-ray Arc

The elongated structure seen in the X-ray arc (Fig. 6 left) straightforwardly suggests that the origin of the X-ray arc is “galaxy gas stripping” caused by ram pressure of the Virgo-ICM (Veilleux et al. 1999). Fig. 4 is a schematic view of this idea. Yasuda et al. (1997) found that the line-of-sight velocity of NGC 4388 is as high as \( \sim 1000 \) km s\(^{-1}\) with respect to the ICM, so that the ISM of the NGC 4388 can be stripped by the strong ram pressure. This fact seems to support the gas stripping origin of the X-ray arc. The gas should be stripped from the galaxy to the opposite direction of the galaxy’s motion, so that NGC 4388 also must have a transverse velocity of \( \sim 1000 \) km s\(^{-1}\). Fig. 4 shows that the hot gas in the X-ray arc shows the lower temperature and the higher density than the ICM. These results can be explained if the gas was heated during the stripping by the ram pressure of the hot ICM (\( \sim 2 \) keV). We might see the moment that the galaxy’s gas is being supplied into the intracluster space.

### References

Figure 1: 2.0-10.0 keV band smoothed image of the Virgo cluster by ASCA mapping (Shibata et al. 2001).

Figure 2: Preliminary spectrum of NGC 4388 nucleus. The spectrum is fitted by an absorbed MEKAL with an temperature $kT$ of 0.4 ± 0.1 keV or an absorbed power-law model with an photon index $\Gamma$ of 1 (0.5-2). $N_H \sim 9 \times 10^{20} \text{cm}^{-2}$ (soft), $3 \times 10^{23} \text{cm}^{-2}$ (hard). Abundance = 0.08 (0.04-2). $L_X \sim 3 \times 10^{42} \text{erg/s}$

Figure 3: Spectra of the extended X-ray emission. (left) Region 1. (right) Region 2.

Figure 4: Schematic view of the interaction between Virgo-ICM and NGC 4388. The observer is located on the right in the same plane as the figure and at a distance of 16.7 Mpc. The value of the transverse velocity (~1000 km/s) is assumed because the gas is stripped to the opposite direction of the galaxy’s motion.
Figure 5: Optical feature of NGC 4388 with Subaru telescope. (left) Narrow band and broad band images of NGC 4388. Hα-band is shown in red, O[III] is in blue and V is in green. The size of this image is 11.6×8.3′. (right) Sketch of the distribution of the Hα-emitting gas around NGC 4388 (Yoshida et al. 2002).

Figure 6: (left) 0.5-2.0 keV band smoothed image of NGC 4388 in the ACIS-S3. Green square line shows the size of ACIS-S3 chip. (right) 2.0-8.0 keV band smoothed image. Each image is smoothed by a Gaussian function with $\sigma = 2$-3.

Figure 7: X-ray contours (0.5-2.0 keV) overlaid on Hα image. X-ray is contoured by the soft band image (Fig. 6 left). The Hα band image is used by only Hα band of Fig. 5.