X-RAY TRIPLE RINGS AROUND THE M87 JETS IN THE CENTRAL VIRGO CLUSTER

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ABSTRACT

The Chandra X-ray data of the central Virgo Cluster are reexamined to reveal a triple-ring structure around the galaxy M87, reminiscent of the spectacular triple-ring pattern of the supernova SN 1987A in the Large Magellanic Cloud. In the sky plane, the two apparent smaller ellipses are roughly aligned along the M87 jets; the larger ring centers at the M87 nucleus and is likely a circle roughly perpendicular to the M87 jet. Certain similarities of these two triple-ring structures might hint at similar processes that operate in these two systems with entirely different sizes and mass scales. We suspect that a major merging event of two galaxies with nuclear supermassive black holes (SMBHs) might create such a triple-ring structure and drove acoustic and internal gravity waves far and near. The M87 jets are perhaps powered by a spinning SMBH resulting from this catastrophic merging event.

Subject headings: galaxies: clusters: individual (Virgo) — galaxies: individual (M87) — galaxies: structure — X-rays: galaxies: clusters

On-line material: color figures

1. INTRODUCTION

Many similar astrophysical phenomena happen on totally different spatial and temporal scales or energy and mass scales. Examples include collimated jets from active galactic nuclei (AGNs) containing supermassive black holes (SMBHs; Begelman 2003), from microquasars containing stellar mass black holes (Mirabel & Rodrı´guez 1999), and from young stellar objects (Ray et al. 1996); dynamical roles of waves in spiral galaxies (Lin & Shu 1984, Fan & Lou 1996; Lou & Fan 1998), in planetary rings (Goldreich & Tremaine 1978), and in galaxy clusters (Fabian et al. 2003a); similar high-temperature atmospheres of the Sun and of stellar mass black hole systems (Zhang et al. 2000); and similar gamma-ray flashes and bursts from explosions of perhaps massive stars at cosmological distances (Mészáros 2001), from solar flares (Haisch et al. 1991), and from the Earth’s atmosphere (Fishman et al. 1994, Feng et al. 2002). We report here the detection of an X-ray triple-ring structure in the core of the Virgo galaxy cluster, most likely associated with the AGN of the galaxy M87 (NGC 4486) and its powerful jet. This triple-ring structure is reminiscent of the spectacular triple-ring pattern of the supernova SN 1987A in the Large Magellanic Cloud (Burrows 1995).

M87 is an active galaxy with relativistic jets in the central Virgo Cluster. The X-ray morphology and spectroscopy of the Virgo Cluster have been studied previously using data from Chandra (Young et al. 2002) and XMM-Newton (Böhringer et al. 2001; Belsole et al. 2001). Combining Chandra, XMM, and ROSAT data, Forman et al. (2004, hereafter F04) studied the Virgo Cluster on various scales to identify cooling flow quenching by an AGN energy input. They noted two protuberant features around the M87 jet and counterjet and referred to them as “cavities” caused by plasma expansions. In this Letter, we reanalyze the Chandra data and focus on the core region around M87. Two smaller ring structures are identified to encircle the cavities noted by F04; a third larger ring centers at the M87 nucleus. We adopt the distance to M87 as ~16 Mpc with 1° for ~78 pc in the image (Whitmore et al. 1995).

2. DATA ACQUISITION AND ANALYSIS

We process the data of two observations (observation ID ObsID 2707 and 352) pointed at the central Virgo Cluster by the Advanced CCD Imaging Spectrometer spectroscopic array instrument on board NASA’s Chandra X-Ray Observatory for a total effective exposure of 119.2 ks. The data are screened for flares where count rates are at least 3σ away from the mean rate in the S1 chip for 2.5–6.0 keV. The exposures before/after screening are 98.7/89.5 ks for ObsID 2707 and 37.7/29.7 ks for ObsID 352. The two screened data sets are merged using the merge_all script in CIAO version 3.0.1 and further corrected with an exposure map.

We avoid the overbrightness of M87 and the jet by extracting the normalized brightness in the range [0, 8%] and renormalizing linearly to [0, 1]; i.e., letting 

\[ B_i = \frac{B_i - B_i^{\text{min}}}{B_i^{\text{max}} - B_i^{\text{min}}} \]

where \( B_i^{\text{min}} \) and \( B_i^{\text{max}} \) be the brightness maps before and after the adjustment, we take 0 \( \leq B_i \leq 0.08 \text{ from a normalized brightness map} \) and renormalize it with 

\[ B_i = B_i / 0.08 \]

The 0.5–2.5 keV image of the central Virgo Cluster is displayed in Figure 1a by a Gaussian smoothing of 1.5 FWHM. To reveal structures of smaller scales in the image, we apply an unsharp mask. A smoothed image \( G \) is obtained by convoluting the raw image \( I \) with a Gaussian function. The sharpened image \( U \) is a weighted subtraction of \( I \) and \( G \), viz., 

\[ U = I + a(I - G), \]

where \( a \) is a constant. By trials, we choose a Gaussian function of 15′ FWHM with \( a = 500\% \). The resulting image of Figure 1b is obtained by smoothing the sharpened image with a Gaussian function of 1.5 FWHM and by adjusting the contrast to enhance visibility of the triple-ring feature; the contrast enhancement is done by displaying only
the image within the brightness range of 15.5%–24%, i.e., 1.24%–1.92% in the original image.

For spectra along the rings, a hardness ratio map is shown in Figure 2 for the central Virgo Cluster where the hardness ratio is defined as 

\[ H = \frac{(c_2 - c_1)}{(c_2 + c_1)} \]

with \( c_1 \) and \( c_2 \) for photon counts in the lower and higher energy bands, respectively (Li 2001). We select 0.5–1.0 and 1.0–2.5 keV as the lower and higher bands. The images are smoothed with a 2\( H^{1/1033} \) FWHM Gaussian function before creating a hardness ratio map in Figure 2.

3. THE TRIPLE-RING STRUCTURE

Two nested X-ray ellipses (Fig. 1b, dashed lines marked as rings 1 and 2) are revealed around the M87 jets. A third larger ellipse can be partially seen (Fig. 1b, dashed line marked as ring 3). The reality of rings 1 and 2 is evident by Figure 1b. Besides the northern and southern diffuse arcs for the initial identification of ring 3, the ring also passes through eight bright X-ray knots (marked by small open arrows) that lend further support for its reality. The X-ray morphology of the Virgo Cluster is fairly complex, with structures on scales from \( \sim 1 \) to 50 kpc (F04). We focus mainly on the triple-ring structure.

Each presumed circular ring fits a projected ellipse using five parameters (see Table 1), viz., the right ascension (R.A.) and declination (decl.), semimajor and semiminor axes, and the inclination angle of the semimajor axis to the local hour circle line. Because the three X-ray rings cannot be readily recognized by our software, errors in these fitting parameters are estimated empirically. We note that position uncertainties are \( \sim H^{1/1031} \) and angular uncertainties are \( \sim H^{5/1034} \).

It is possible that the observed ellipses are projections of circular rings in the sky plane. We reconstruct three-dimensional orientations of the three circular rings. The jet orientation may be taken as either 43\( ^\circ \) (Biretta et al. 1995) relative to the line of sight (LOS) away from us or, more likely, 15\( ^\circ \) (within 19\( ^\circ \) as inferred by Biretta et al. 1999). The angle of the projected jet to the local hour circle line is \( \sim 70^\circ \) (Fig. 1). Thus, the angle \( \Phi \) (see Table 1) of the reconstructed circular ring normal to the jet direction (if 43\( ^\circ \) to LOS) is 61\( ^\circ \), 51\( ^\circ \), and 9\( ^\circ \) for rings 1, 2, and 3, respectively. This means that ring 3 is likely a circular ring nearly perpendicular to the M87 jet. For a jet orientation of 15\( ^\circ \) to the LOS, the corresponding angles \( \Phi' \) of the ring normal to the jet (see Table 1) are 55\( ^\circ \), 33\( ^\circ \), and 22\( ^\circ \), respectively. The derived values of \( \Phi \) and \( \Phi' \) for presumed “circular” rings 1 and 2 are fairly large; these two rings might be elliptical in the three-dimensional space or their orientations are not perpendicular to the jet. Our estimate excludes the possibility that the elliptical shape of rings 1 and 2
is caused by relativistic projection effects if the two circular rings expand radially away from the jet axis while moving apart from each other relativistically along the line connecting the two ring centers, because by special relativity the ring would be elongated transverse to the jet direction. We note that ring 3 passes through eight X-ray bright knots with its center located exactly at the M87 nucleus. The chance of such a coincidence is small. As projected, rings 1 and 2 roughly align along the direction of the M87 jet and counterjet; their intrinsic elliptical (instead of circular) shapes in three-dimensional space are plausible. Given the relatively small angle of ring 3 normal to the jet (9° or 22°), one may qualitatively regard ring 3 as circular and perpendicular to the jet.

4. SPECTROSCOPY OF THE THREE RINGS

From Figure 2, the softest regions locate (i) around the jet within a ~20° radius sector from west to north of the nucleus, (ii) at an extended arc coincident with the east portion of ring 1 from north to south of the nucleus, (iii) at a short arc coincident with ring 3 about ~30° away from the nucleus in the northwest, and (iv) at some extended filaments southeast of the nucleus outside the three rings. By comparing Figure 2 with the Hα + [N II] emissions of the central Virgo Cluster (Sparks et al. 1993), we find that the soft regions (i) and (iv) are correlated with Hα + [N II] filaments. Similar correlations were also found in the Perseus Cluster (Fabian et al. 2003b), indicating that intracluster gases become cooler when adjacent to the filaments due to thermal conduction. The association of regions (ii) and (iii) with rings 1 and 3, respectively, is interesting, with region (ii) being more striking. A harder spectrum may correspond to a higher temperature. Different temperatures along ring 1 indicate that X-ray emissions may not be caused simply by a high density of electrons alone but may involve supersonic shock flows from the AGN. Other parts of rings without temperature difference relative to the surroundings might indicate subsonic flows.

Energy spectra are derived from two segments of ring 1, viz., the east part identified with region (ii) and the west part. To compare the spectra in these two parts with their environments, the source region is partitioned as an elliptical annulus along ring 1 with a width of ~4° and a background region of a bigger elliptical annulus outside 5° of ring 1 with a width of ~2°. The source and background regions are separated into two parts by a straight solid line in Figure 2.

In Figure 2, the east part carries features, while the west part blends with the environment. We adopt a hot diffuse gas emission model (VMEKAL) to fit the spectra of both parts, with free parameters of equivalent hydrogen column, temperature, and elemental abundances of O, Ne, Mg, Si, S, and Fe. The fitting is carried out using XSPEC version 11.3. The best-fit temperatures are 0.74 +0.04 −0.05 keV (χ²/dof = 71/54) for the east part and 1.32 +0.14 −0.13 keV (χ²/dof = 53/55) for the west part. A remarkable difference in plasma temperature can be seen from energy spectra using the hardness ratio map in Figure 2. In contrast, only the central ring of SN 1987A can be resolved by Chandra using a subpixel technique (Burrows et al. 2000; Park et al. 2002; Michael et al. 2002). As its X-ray spectrum may be fitted by a plane-parallel shock model, the central ring of SN 1987A is thought to involve an expanding blast wave. By this clue, we attempt to fit the spectra of both east and west parts of ring 1 (Fig. 1b) using the plane-parallel shock model (VPSHOCK) with the same free parameters of elemental abundance indicated above. The west part spectrum does not fit the plane-parallel model well with a large χ²/dof ~ 5, while the east part spectrum fits well with the shock model. The best-fit temperature is 0.71 +0.04 −0.04 keV (χ²/dof = 77/53), consistent with the hot plasma model. This suggests that ring 1 may involve a blast wave where the west part might have been thermalized with the surroundings and the east part might be in the process of being thermalized. For the east part, the best-fit abundances of elements O, Si, S, and Fe in the thermal model are systematically lower than that in the west part. The enhancement of abundances in the warmer region may indicate more active nuclear processes in the past, perhaps caused by the thermalization in the west part. The similar temperature-abundance correlation is also found with XMM in the inner region for radius ≤1′ (Böhringer et al. 2001) and for the two large-scale arms (Belsole et al. 2001). Because of uncertainties in estimating abundances with Chandra data for the fine structures, we refrain from more detailed comparisons with previous results of XMM for the larger structures.

5. DISCUSSION

The triple-ring pattern revealed in the central Virgo Cluster is the only one observed since the discovery of triple rings in SN 1987A (Burrows 1995). The ring sizes in the Virgo Cluster are several thousand times larger than those of SN 1987A. The triple-ring structure of SN 1987A has been simulated in terms of interacting winds near the end of stellar evolution. According to Tanaka & Washimi (2002), during the star’s red supergiant phase, slower winds persist. Prior to the supernova explosion, the red supergiant somehow evolved into a blue supergiant that drove faster winds, MHD interactions of fast and slow winds from a rotating star produce the triple-ring structure in SN
We suspect that a catastrophic merging event around the M87 nucleus might be responsible for the triple-ring structure revealed here. Merging of two SMBH systems has been proposed to drive the observed X-shaped radio lobes (Merritt & Ekers 2002). In this scenario, a “slower wind” was present before the merging begins, e.g., a mixture of galactic winds from two merging galaxies. A “faster wind” was then driven during the merging process. It has been suggested that an active AGN phase occurred in the core region of M87 at about 10^8 yr ago (Kaiser 2003); perhaps this AGN was triggered by the merging event discussed above, when a significantly higher accretion rate was provided by the merger. The merger may fuel both the radiation energy output of the AGN and the growth of the SMBH in the center; a huge amount of high-energy radiation shines the triple rings in X-ray bands. It is also plausible that the resulting SMBH spins rapidly to power the highly collimated M87 jets (Blandford & Znajek 1977).

F04 revealed two expanding cavities around the M87 jet and counterjet, enclosed within our rings 1 and 2, respectively. By different external pressures, they inferred that the far front of the cavities is mildly supersonic while the inner part, close to the nucleus, is collapsing. We suggest that these two rings are actual rings instead of projections of prolate spheres, because when two cavities collide into each other it is hard to maintain their spherical shapes in the spatially overlapping portions of the two spheroids, and consequently their projections cannot be viewed as two complete and nested rings. We further suggest that when the jets form, they push materials around and drive powerful blast waves of ring shapes.

Qualitatively similar central structures are present in the clusters Perseus (Fabian et al. 2003a), Hydra A (McNamara et al. 2000), Centaurus A (Kraft et al. 2002; Karovska et al. 2002), and Virgo (F04). Physically, core activities can excite large-scale acoustic waves (p-modes) and internal gravity waves (g-modes) in a deep gravitational potential well of the central galaxy cluster (Lou 1995). Cluster core activities can be either violent and sporadic or sustained at a level or a combination of both. Depending on the phase of acoustic wave propagation and on physical properties of core environment, we may observe various X-ray morphologies superposed onto a smooth luminous core. Beautiful acoustic rings or arcs have been revealed in Perseus (Fabian et al. 2003a) and in Virgo on larger scales (F04). Intense core X-ray emissions tend to induce inflows of gas that perturb the dark matter via gravity. The violent relaxation proceeds in a sound-crossing timescale (Lynden-Bell 1967). This could be a persistent source of p-modes and g-modes in a cluster core. By such wave and Laudau-damping processes, slowly inward drifting gas and dark matter are virialized to sustain X-ray losses from hot electron gas. As a cluster core may involve magnetic field of strengths up to ~30-40 μG, MHD waves should also play significant roles. On the basis of the hardness ratio map and the energy spectra fitting, we infer that only parts of rings 1 and 3 involve supersonic shock flows and are in processes of being thermalized with the surroundings. By this reasoning, other parts without apparent difference with surroundings might have been thermalized already. In summary, we hope that the triple-ring structure of M87 in the central Virgo Cluster will stimulate more theoretical, simulation, and observational studies of MHD flow, wave, and shock interactions.

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