The Gas Dynamics of NGC 4472

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Abstract.
We present preliminary results from a 100 ks XMM-Newton observation of the hot gas in the nearby massive early-type galaxy NGC 4472. This galaxy is the central member of a group of galaxies that is falling into the Virgo cluster. We find several structures in the gas indicative of both a complex interaction with the ICM of the Virgo cluster and a previous epoch of nuclear activity. First, we detect a contact discontinuity and ram-pressure stripped tail extending at least 50 kpc from the nucleus. There is no evidence for a shock at the contact discontinuity, indicating that the infall must be transonic or subsonic. The density of the external gas is sufficiently large as to suggest that NGC 4472 is falling into M87 along a still-collapsing gas filament. Second, we detect two pairs of cool filamentary arms that extend 25 kpc to the east and southwest of the nucleus. One of these filaments was detected in an earlier Chandra observation and is known to have a sharp, well-defined interface with the ambient medium. These filaments are likely the remnants of cold gas that has been entrained by buoyant radio bubbles from a previous epoch of nuclear activity.

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INTRODUCTION

Chandra and XMM-Newton have opened new windows into the study of the gas dynamics associated with the inflation of radio lobes in active galaxies, the dynamics of galaxy merging, and the formation of structure. A wide variety of features have been observed in the hot gas of early-type galaxies and groups including shocks, cold shells, filaments, contact discontinuities, cold fronts, and ram-pressure stripped tails. In particular, many of the Virgo cluster galaxies have been studied in detail due to their proximity and diversity of structures.

In this paper, we present results from a 100 ks XMM-Newton observation of the hot gas in the massive early-type galaxy NGC 4472. NGC 4472 is the dominant galaxy of a large group that is falling into the Virgo cluster and lies $\sim$1.35 Mpc from M87 (roughly the virial radius). Our previous Chandra/ACIS-S observations showed twin cavities $\sim 2'$ from the nucleus coincident with radio lobes as well as a surface brightness discontinuity 21 kpc north of the nucleus attributed to a contact discontinuity between the NGC 4472

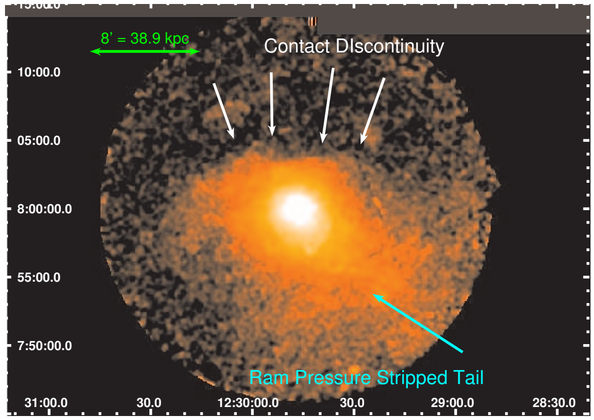

FIGURE 1. Smoothed, exposure corrected image of NGC 4472 in the 0.5-2.0 keV band (MOS1+2 cameras). The approximate positions of the contact discontinuity between the NGC 4472 gas and the Virgo cluster gas is shown with the white arrows, and the ram pressure stripped tail by the blue arrow.

group gas and the Virgo cluster gas [1]. In this paper, we assume a distance of 16 Mpc to NGC 4472 ($1'$=4.65 kpc).

ANALYSIS

An exposure corrected XMM-Newton image (MOS1+MOS2 coadded) of the diffuse gas in NGC 4472 in the 0.5-2.0 keV band is shown in Figure 1. Several features in this image are immediately evident. First, there is a sharp, but irregular, surface brightness discontinuity to the north and northeast of the nucleus. M87 lies approximately 4° north of NGC 4472. We identify this discontinuity as a contact discontinuity between the NGC 4472 group gas and the Virgo cluster gas. The flux beyond the north of the discontinuity is significantly in excess of the dark sky background and is due to large scale emission from the Virgo cluster. Second, a ram-pressure stripped tail extends at least 50 kpc to the southwest of the nucleus, confirming the ROSAT result [2]. It is interesting that even at the virial radius of the Virgo cluster, the effects of ram-pressure stripping can be dramatic.

The X-ray emission in a softer band (0.5-1.0 keV) is shown in Figure 2. Four filamentary arms are present in the soft band emission, two to the northeast of the nucleus and two to the southwest. These arms are not visible in the broad band image (Figure 1) or in a harder (1.0-2.0 keV) band image (not shown). One of the filamentary arms to the southwest is coincident with a sharp surface brightness discontinuity seen in the Chandra/ACIS-S observation [1]. We created a temperature map, shown in Figure 3, from the centroid of the Fe L line complex. This centroid is known to be a sensitive temperature diagnostic [3]. The filamentary arms are clearly cooler than the surrounding gas, and at roughly the same temperature as the gas in the core of NGC 4472.

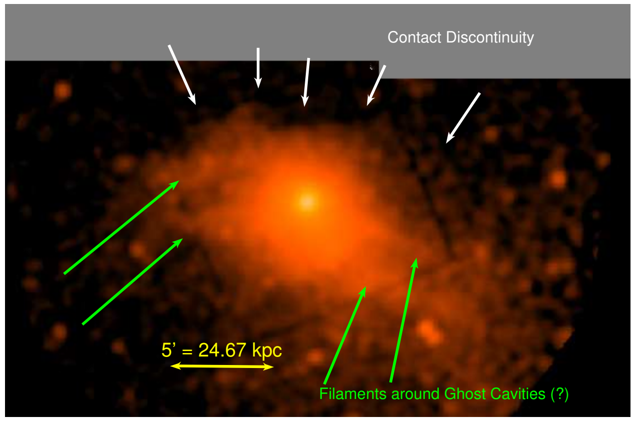

FIGURE 2. Smoothed, exposure corrected image of NGC 4472 in the 0.5-1.0 keV band (MOS1+2 cameras). Note the presence of the filamentary arms (green arrows) in this softer band image.

INTERPRETATION

The contact discontinuity and ram-pressure stripped tail clearly demonstrate that NGC 4472 is falling into the Virgo cluster. The velocity of infall can, in theory, be estimated by the pressure ratio between the gas interior and exterior to the contact discontinuity [4]. We use the XSPEC model *projct* to deproject the density and temperature profile of the gas interior to the discontinuity. We find T_{int}=1.2$\pm$0.05 keV and $n_{int}\sim10^{-3}$ cm^{-3}. The complication to this analysis is determining the gas density (and hence pressure) of the gas exterior to the discontinuity. If we extrapolate the density profile of the Virgo cluster determined by ROSAT [5] in the central 250 kpc, we find that n_{ext}=10^{-4} cm^{-3} at the distance of NGC 4472 (1.35 Mpc). The temperature of this gas determined from a rectangular region in the XMM-Newton data is $\sim$1.6$\pm$0.2 keV. The pressure ratio, p_r, is then $\sim$7.5, and the velocity of infall is $\sim$1900 km s^{-1}, or Mach 3.5. This infall velocity is unrealistically large for a group at roughly the virial radius as it greatly exceeds any reasonable peculiar velocity for the group, and there is no evidence for a shock. More likely the density of the gas exterior to the jump is much larger than estimated by the ROSAT extrapolation. Examination of the large scale image of the Virgo cluster suggests that NGC 4472 is falling in toward M87 along a filament of enhanced X-ray emission. In fact, the dynamics are probable even more complex because the gas in this Virgo cluster filament is probably falling back into the gravitational potential of NGC 4472. This phenomenon is required to explain the anomalously large velocity of infall of the Bullet cluster [6]. In this scenario, the pressure jump reflects the relative velocity of the NGC 4472 group to this infalling gas, not to the infall velocity to M87.

Interaction with the Virgo cluster gas is, however, not likely to have created the filamentary arms. Hydrodynamic simulations show that complex, subsonic can motions can be induced in the dense cores of merging galaxies. The low entropy material at the center of the merging galaxy will be transported to a thin shell just behind the contact discontinuity in the direction of infall [7]. A Chandra observation of the cluster gas associated with the radio galaxy 3C 28 supports this picture [8]. This does not appear to be what is happening in NGC 4472, however, the arms lie along the axis of infall in both

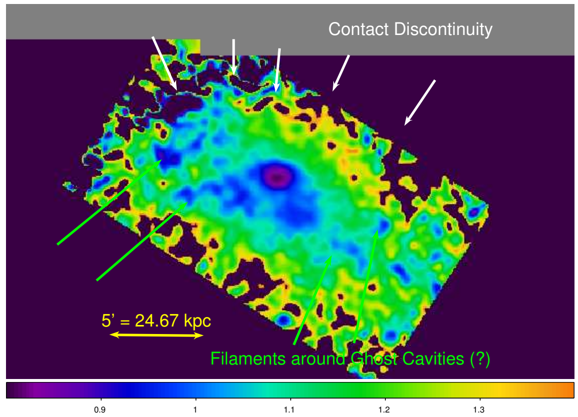

FIGURE 3. Temperature map of NGC 4472 created using the centroid of the Fe L line. The white arrows denote the approximate position of the contact discontinuity between the NGC 4472 group gas and the Virgo cluster gas. The filamentary arms that may have been created by the buoyant rise of a dead radio lobe are shown with the green arrows.

directions. These arms are more likely the result of a previous epoch of nuclear activity. Similar features have been observed in Chandra observations of M87 [9] and are the result of the buoyant rise of a radio bubble that drags low entropy gas from the core into the halo. There is no evidence for a previous epoch of nuclear activity in the radio band, so these are ghost cavities in which energy loss (either via radiation or adiabatic expansion) has shifted the bulk of the emission below the hundreds of MHz frequency. These bubbles lie along the northeast/southwest axis, different than the east-west axis of the bubbles in the current nuclear outburst. This again is similar to the situation in M87 where the larger scale bubbles do not lie along the same axis as those of the current outburst. The total energy (bubble enthalpy) of this previous outburst is $\sim 2\times10^{56}$ ergs assuming that the ghost cavities have the shape of a prolate spheroid.

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