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MOLECULAR GAS PROPERTIES UNDER ICM PRESSURE IN THE CLUSTER ENVIRONMENT

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ABSTRACT

We present 12CO (2−1) data for four spiral galaxies (NGC 4330, NGC 4402, NGC 4522, NGC 4569) in the Virgo cluster that are undergoing different ram pressure stages. The goal is to probe the detailed molecular gas properties under strong intra-cluster medium (ICM) pressure using high-resolution millimeter data taken with the Submillimeter Array (SMA). Combining this with Institut de RadioAstronomie Millimétrique (IRAM) data, we also study spatially resolved temperature and density distributions of the molecular gas. Comparing with multi-wavelength data (optical, H I, UV, Hα), we discuss how molecular gas properties and star formation activity change when a galaxy experiences H I stripping. This study suggests that ICM pressure can modify the physical and chemical properties of the molecular gas significantly even if stripping does not take place. We discuss how this affects the star formation rate and galaxy evolution in the cluster environment.

Key words: galaxies: clusters: intracluster medium; galaxies: evolution; galaxies: ISM; galaxies: spiral; galaxies: star formation; submillimetere: galaxies

1. INTRODUCTION

Cluster galaxies are distinct from field galaxies. In general, galaxies tend to be redder and more passive in environments of higher density such as cluster cores (e.g. Dressler 1980). Various environmental processes might be responsible for this phenomenon. In particular, ram pressure stripping due to the hot gas in the cluster has been suggested as an efficient way to strip the interstellar medium from galaxies, making them evolve passively (Gunn & Gott, 1972; Crowl & Kenney, 2008).

Neutral hydrogen studies using single-dish telescopes find that cluster spirals are H I-poor compared to field galaxies with similar sizes and morphologies (e.g. Giovanelli & Haynes 1985). As shown by H I imaging data (e.g. Chung et al. 2009), a number of H I-deficient galaxies are not only severely truncated within the stellar disk but are also disturbed (e.g. NGC 4522; Kenney et al. 2004). These are good examples showing that indeed H I gas can be stripped by the ICM wind.

Once H I gas is removed, the star formation activity on the disk may be affected. In fact, the star formation rate of Virgo spirals measured by Koopmann & Kenney (2004a) is a factor of 2.5 smaller than their field counterparts. Many Virgo galaxies that are stripped of H I within the stellar disk also reveal a small Hα disk, unlike field galaxies (Koopmann & Kenney, 2004b).

On the other hand, it is still under debate whether molecular can gas also be stripped by the ICM wind as for H I or not. In a CO survey of a large sample of galaxies, Kenney & Young (1989) find no significant difference in CO content between field galaxies and cluster members. In fact, it is expected to be more difficult to strip molecular gas since it is higher in surface density and more tightly bound toward the galactic center when compared with atomic gas. Considering, however, that molecular gas is more important for forming stars, the fact that cluster galaxies have comparable molecular gas masses is puzzling, since the star formation rate does change with the environment.

Meanwhile, Fumagalli et al. (2009) provide evidence that galaxies stripped of H I within the stellar disk are also deficient in molecular gas, suggesting that ram pressure can also affect molecular gas. In fact, Vollmer et al. (2008) find CO gas in extragalactic space which is likely to have been pushed out by the ICM pressure. Therefore, the question is whether ram pressure can change molecular gas properties and hence star formation activity even if the molecular gas does actually not get stripped away.

In order to study how molecular gas properties change under strong ICM pressure in the cluster environment, we investigate high resolution CO data of a sample of four galaxies experiencing different strengths of ram pressure in Virgo.

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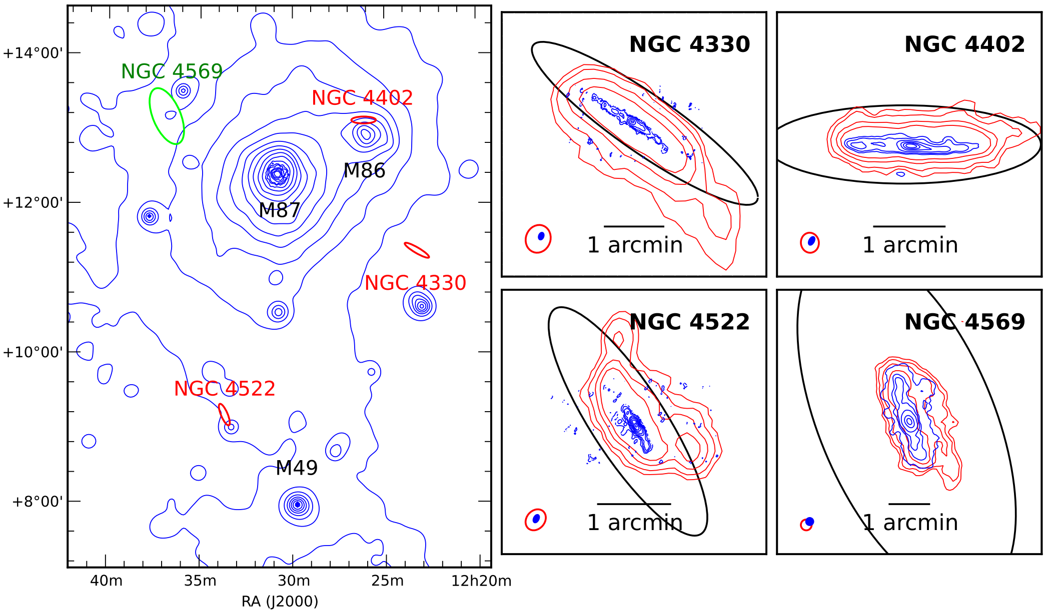

Figure 1. On the left, the locations of four Virgo galaxies at various H I stripping stages are shown overlaid on the ROSAT X-Ray map (blue contours, Böhringer et al. 1994). Ellipses represent $D_{25} \times 5$ in the optical B band. 12CO (2−1) data were taken using the SMA except for NGC 4569 (noted in green), for which we facilitate the data from 'HERACLES: The HERA CO Line Extragalactic Survey'. On the right, 12CO (2−1) contours are shown in blue and H I distribution are shown in red. Black ellipses represent the optical size (D_{25} in B-band). The synthesized beams of H I (red) and 12CO (blue) are shown in the bottom left corner of each box.

2. VIRGO SPIRAL SAMPLE AND OBSERVATIONS

As the nearest large galaxy cluster, Virgo is an ideal place to study individual galaxies undergoing various processes in great detail. Based on H I images, we have selected four spirals that are currently experiencing ram pressure with different strengths. NGC 4330 is likely entering the core region of Virgo for the first time, and appears to be at a relatively early stage of H I stripping (Chung et al., 2007). NGC 4402 and NGC 4522 are undergoing active stripping, but in different locations within the cluster (Kenney et al., 2004; Crowl et al., 2005). NGC 4569 is likely to have gone through the cluster core a few Myr ago and is now on its way out to a lower density region (Vollmer et al., 2004). These four galaxies show peculiar H I morphology but not are optically disturbed, indicating that these galaxies are being affected by the cluster gas not tidal interactions. These make a good sample to study the molecular gas properties in galaxies undergoing ICM pressure.

Using the Submillimeter Array (SMA), we observed 12CO J=2−1 (ν_{rest}=230.538 GHz) and 13CO J=2−1 (ν_{rest}=220.398 GHz) of three galaxies (NGC 4330, NGC 4402, NGC 4522) in March 2010 and March 2011 in the subcompact configuration. We skipped NGC 4569 which has well resolved 12CO (2−1) archival data from 'The HERA CO-Line Extragalactic Survey', from the IRAM 30m telescope, (Leroy et al., 2009). Aiming to cover half the stellar disk, we mosaicked 3-5 points depending on the optical size of individual galaxies. The SMA data were calibrated using MIR (Qi, 2012). The continuum was subtracted and final image cubes of 5km s^{-1} resolution were made using the MIRIAD package (Sault et al., 1995). In addition, we obtained 12CO (1−0), (2−1) and 13CO (1−0), (2−1) data of NGC 4402 using the IRAM 30m single-dish radio telescope in OTF mapping mode. We targeted this galaxy since it is the only one of the SMA sample that is detected in 13CO (2−1). We are currently analyzing these four lines to probe the distribution of molecular gas density and temperature using a non-LTE model.

3. RESULTS

On the right of Figure 1, the H I and CO distributions of the sample are shown in red and in blue, respectively. The CO contours represent our SMA 12CO (2−1) emission, except for NGC 4569, which comes from 'The HERA CO-Line Extragalactic Survey, (Leroy et al., 2009). The optical disk is indicated by black ellipses. A one arcmin bar (∼4.7 kpc at the distance of Virgo, 16 Mpc, Yasuda et al. 1997) is shown at the bottom of each box. The H I disks of these galaxies are all truncated within the stellar disk and are highly asymmetric, indicating active ram pressure stripping due to the cluster medium.

Our SMA maps do not show any emission that extends beyond the stellar disk. The SMA flux of NGC 4402 is comparable to the single-dish measurement. No single-dish flux has been published for NGC 4330, however, the CO extent seen in our SMA data is similar to what is shown in the IRAM data (Vollmer et al., 2012). Therefore it is unlikely that we are missing much CO

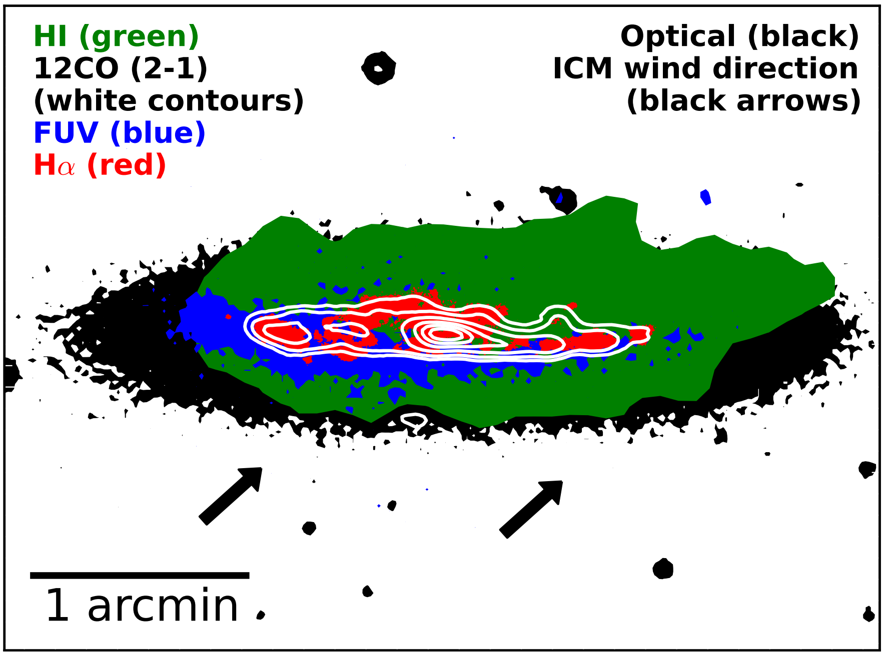

Figure 2. The 12CO is more extended in the same direction as the H I gas (in the west; right side) (VIVA, Chung et al. 2009), while its old stellar disk (DSS2 blue) is not disturbed. Both 12CO gas and H I gas are compressed in the south. However, its optical disk do not show disturbed features. The *FUV* emission (Galaxy Evolution Explorer; GALEX, Gil de Paz et al. 2007) is strongly enhanced along the southern part of 12CO. It is possible that the star formation is triggered by molecular gas compression due to the ICM pressure. The extents of Hα (GOLDMine, Gavazzi et al. 2003) and 12CO are roughly coincident with each other. It is within the inner region of the molecular gas disk where most star formation is taking place. The ICM wind direction is indicated with black arrows.

emission in these two galaxies. The SMA CO flux of NGC 4522, however, is smaller than the IRAM CO flux by a factor of at least a few 2.8. In fact, NGC 4522 reveals extraplanar CO gas in its IRAM OTF data, and our discussion on this galaxy is limited to the central part of the molecular gas disk.

We find that molecular gas does not get pushed as much as atomic gas by ICM pressure. However, the SMA data of our sample showing asymmetry and disturbances suggests that ram pressure due to the ICM can affect the deeper regions inside the molecular gas disk. High resolution CO images of the central region in field galaxies show morphological asymmetries at some level (Helfer et al., 2003) but the asymmetry of these galaxies appears to be closely related to the H I morphology, which reflects characteristics of ram pressure such as the ICM wind direction and the acting angle. Evidence that the peculiarities in the molecular gas of this sample are caused by the ICM pressure is also found in the CO kinematics (Lee et al., in preparation).

The asymmetric CO morphology of NGC 4402 is correlated with other wavelength data, including *UV* and Hα, which are indicators of recent star formation activities as shown in Figure 2. The diffuse H I tail (green) with no signs of disturbance in the stellar disk (black) clearly indicates that the galaxy is experiencing strong ICM winds from the southeast as indicated with arrows in Figure 2. There is a strong enhancement of *FUV* emission (blue) along the southern part of the disk where the ICM wind is acting. Hα emission (red) shows an even better correlation with CO (white contours) in the overall morphology and extent. The gas compression due to the ICM pressure might be responsible for this locally enhanced star formation (Fujita & Nagashima, 1999).

Generally, these morphological correlations among multi-wavelength data strongly suggest that the molecular gas and recent star formation have been also affected by ICM pressure. Even if the molecular gas is not stripped from the stellar disk by the ICM pressure as H I is, molecular gas can be still disturbed, and the impact can reach to the galactic center. Consequently the molecular gas kinematics will differ from those of field spirals, which can change star formation properties as well.

The ICM pressure may change the physical properties of molecular gas in Virgo spirals. In order to constrain the physical conditions of molecular gas in these galaxies, we are currently probing the density and the temperature of the molecular gas using multiple molecular lines (12CO, 13CO (2−1) and (1−0)) obtained using the SMA and the IRAM 30m telescope. Our preliminary results are presented in Figure 3. Different colors indicate the solutions coming from the ratio between different pairs of molecular lines. The CO data with different resolutions have been convolved to the largest beam size. Figure 3 is the result of non-LTE modeling of only one region in NGC 4402. The calculation of the full

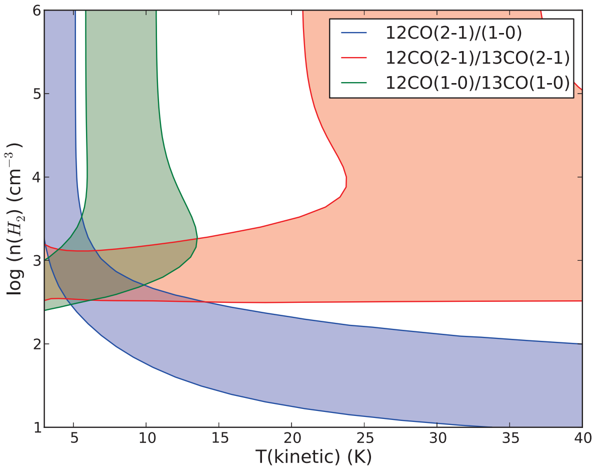

Figure 3. The results of non-LTE modeling of one region of NGC 4402 based on four lines: 12 and 13CO (2−1) and (1−0). Different colors show the possible ranges of density and temperature of molecular gas diagnosed by the ratios between any two CO lines among the four. Using three CO ratios, the physical state of the molecular gas can be well constrained. Currently we are working on the full distributions of the temperature and the density of NGC 4402.

distribution of the density and the temperature of the molecular gas is in progress, and is expected to bring us better understanding of how ICM pressure affects different phases of the interstellar medium, how it changes star formation rate, and hence the galaxy evolution.

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