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Cold Molecular Gas in Abell 1795

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A CO emission line survey in central cluster galaxies with cooling flows had been performed with the IRAM 30m telescope. We have detected cold molecular gas in 6 cluster cores leading to M_{gas} up to a few 10^{10} $M_\odot$ (Salomé & Combes 2003), in agreement with previous detections claimed by Edge (2001). We focus here on one of these detections, the cluster of galaxies Abell 1795, which shows a remarkable filamentary structure, seen both in X-ray and Hα. We report IRAM interferometer maps of CO(1-0) and CO(2-1) rotational lines of the cluster center. The cold gas morphology is shown and appear to be associated with a cooling wake. The total cold gas mass derived with the 30m telescope was 4.3×10^9 $M_\odot$ and is likely to be even higher since the ICM metalicity is 0.2–0.3 solar. We find now that most of the emission is extended, as only 25% of the single dish flux detected is retrieved by the interferometer. Position-velocity maps are also presented and reveal a velocity gradient. The cold gas kinematics and morphology is very similar to what was found through Hα, supporting the association between the cold gas and the optical filament. The optical nebulosities, aligned with the cD orbit, are intimately related to the radio jets and lobes and the material detected here is certainly fueling the star formation (also aligned with the lobes). Even if some heating mechanisms are present, these millimetric CO maps show an effective cooling to very low temperatures indeed occurs.

1. Introduction

Abell 1795 is a rich cluster of galaxies. Recent X-ray observations with the X-ray satellites *Chandra* and *XMM-Newton* confirmed the gas temperature is dropping towards the center (Tamura et al. 2001; Ettori et al. 2002). Fabian et al. (2001) discovered a long ($\sim 40''$) North-South filament with *Chandra*. The X-ray filament is coincident with an Hα+N[II] filament previously found by Cowie et al. (1983). The radiative cooling time of the gas in the filament is similar to its dynamical age (length/velocity). The cD, a little South of the head of the filament is not at rest in the cluster potential and is probably oscillating around the cluster core. A possible explanation (Fabian et al. 2001) is that the filament is a cooling wake : during the cooling time, the large scale hot gas sees the minimum of potential as a straight line along the cD that may accrete the cooled gas.

X-ray spectral analyses by Ettori et al. (2002) conclude that the gas in the core of Abell 1795 cools radiatively in $\sim 3.8 \times 10^8$yr in the central 10 kpc radius. The cooling radius where the cooling time reaches a Hubble time is at about 200 kpc and the mass deposition rate at this radius is of about 100 $M_\odot$/yr. In the model the authors have adopted (i.e. a multiphase component model with extra absorption), the mass deposition rate within a $10''$ radius is only 7.9 ± 2.4 $M_\odot$/yr and the cool emission is suppressed by an intrinsic absorption found to be of about 1.8×10^{21}cm^{-2} in the same region. IRAM 30m telescope detection in Abell 1795 of a very cold component inside a $11''$ radius region (Salomé & Combes 2003) leads to a molecular hydrogen column density of 2.1×10^{21}cm^{-2} in good agreement with what is expected from X-ray absorption. Moreover, the cold gas mass inferred is $\sim(4.8 \pm 0.6) \times 10^9$ $M_\odot$, that could be deposited in $\sim$4.0-10 10^8yr, taking into account X-ray mass deposition rates. This is quite similar to the cooling time of the gas in the central region ($t_{\rm cool} \sim (3.4 \pm 0.6) \times 10^8$ yr). It is possible that the gas detected with the single dish telescope is the sink of cold gas deposited continuously by the cooling flow.

Actual scenarios tend to consider an intermittent cooling with re-heating phases that could be linked to the radio activity of a central source commonly found in cooling flow clusters of galaxies. The aim of observations carried out with the Plateau de Bure interferometer and presented here was to identify the cold gas emitting region in the cluster core and to study its dynamics in order to discriminate a galactic origin and to look for more evidences of a cooling flow residual. The next section presents the interferometer and observations characteristics. Sections 3 and 4 describe the morphology and the dynamics of the cold molecular gas detected. In section 5, we discuss the place of this cold gas within the cooling flow and section 6 are conclusions.

Throughout this paper, we assume $\Omega = 0.3$, $\Lambda = 0.7$ and $H_0 = 70$ km s^{-1}Mpc^{-1}.

2. Observations and Data Reduction

Mapping the cold molecular gas emission was done with the IRAM Plateau de Bure interferometer through CO(1-0) and CO(2-1) rotational lines. Seven partial observing runs were carried out during winter and spring 2002. The total integration time is 43 hours. Frequencies were centered on the central cD galaxy redshift

($z = 0.0631$), at 108.413 and 216.822 GHz, respectively . Observations were made with 5 or 6 antenna in the compact configurations C and D which gave a quite good spatial resolution: $3\farcs26\times3\farcs23$ at 2.7mm and $1\farcs81\times1\farcs31$ at 1.3mm. Primary beams are $43''$ in CO(1-0) and $22''$ in CO(2-1) which correspond to the central 56.5 and 28.9 kpc (i.e. $1'' = 1.31$ kpc). The IRAM interferometer is equipped with 8 independent, nearly identical correlator units. Four contiguous bandpasses of 160 MHz bandwidth covered 580 MHz, that is, $\sim$1600 km/s and 802 km/s in CO(1-0) and CO(2-1), respectively. The observing spectral resolution was 1.25 MHz. To improve signal-to-noise, we smoothed into channels of 89 km/s and 44 km/s since the expected line width was $\sim$500 km/s from IRAM 30m single dish observations. Reduction was made in the IRAM headquarters, Grenoble, in December 2002 and analyzed with the GILDAS package to build 16 velocity channels maps. The total emission is presented in integrated maps (summed over all the velocity channels). Position-Velocity (P-V) maps were then built to explore the dynamics of the cold gas.

3. **Cold Molecular Gas Morphology**

3.1. *Continuum Emission from 4C+26.42*

The central cD galaxy in Abell 1795 hosts the radio source 4C+26.42, well described by van Breugel et al. (1984) who observed the radio galaxy through 20cm, 6cm and 2cm wavelengths with the VLA. It is a small and bright Z-shaped radio source. Various component are identified, principally a nucleus and two lobes bent by almost 90 degrees. The continuum emission in the nucleus is detected at 3mm. It is consistent with the expected radio source synchrotron emission, with decreasing slope of $\alpha \sim -1$ No continuum emission is detected at 1.3mm with the actual PdB sensitivity.

3.2. *Extended Cold Gas*

CO(1-0) and CO(2-1) rotational lines are detected. The line ratio is consistent with an optically thick gas with somewhat sub-thermal excitation, due to an average low density. After continuum subtraction, integrated maps have been built by integrating over the whole range of covered velocities at both wavelengths. Results are presented on Fig. 3.2. CO emission is clearly detected through CO(1-0) and CO(2-1) emission lines. The IRAM 30m detection is confirmed. We can see there are two bright features identified in both lines: one at the field center (i.e. at the galaxy position) and another one at $\sim4''$ North-West from the cD (NW hereafter). The two distinct regions correspond to the two regions observed in U-band excess and associated to star formation found by McNamara et al. (1996). The a large reservoir of cold gas discovered in the core of Abell 1795 fuels the star formation there (Pinkney et al. 1996). Moreover, the cold gas in the central $10''$ superpose exactly to the Hα imaged by van Breugel et al. (1984) as shown on Fig. 3.2. Finally, the NW region peaks at the brightest X-ray emission region, which is identified as the region where the cooling time of the gas is the shortest. The S/N is stronger in CO(2-1) than in CO(1-0) and the shape of the cold gas region is well identified in CO(2-1). But the limited primary beam at 1.3mm ($22''$) avoid the detection, if present, of gas at larger radii. The CO(1-0) emission is too faint to be compared to the large North-South filament seen through X-ray and Hα. Nevertheless a South-West structure seems to appear in emission, which suggests the possible presence of cold gas towards the South. More observing time is required to try to map the southern filamentary region with IRAM interferometer and confirm the CO extension towards the South.

We have compared the CO emission lines obtained here with previous measurements made with the IRAM 30m telescope. A $22''$ and an $11''$ region have been selected in the PdB images in CO(1-0) and CO(2-1). Emission line maps have then been corrected for beam effects and spectra integrated over all the region have been extracted. The total flux obtained with the interferometer is much lower than that found with the single dish telescope: only 25% and 44% are retrieved at 3mm and 1.3mm respectively. That means the emission is certainly extended and filtered by the interferometer. A faint two peaks behavior also appear in the spectra, clearly seen in CO(1-0), but also in CO(2-1) even if the smaller velocity range limits the comparison. Two components in velocity seems to be present: one centered on the cD velocity and one at ~-300 km/s. To study these peculiar dynamics, Position-Velocity diagrams have been made.

4. **Cold Molecular Gas Dynamics**

4.1. *Position-Velocity Diagrams*

Two P-V diagrams taken along the axis of maximum emission (PA = $27°$) are presented in Fig. 2 and Fig. 3. The presence of two components in velocity, suggested by the integrated spectra is confirmed here: a first one centered on the galaxy position, at the cD velocity (i.e. 0 km/s) less apparent at 3mm, and a second one, bright in both lines peaked at $\sim4''$ North, at a velocity ~-350 km/s. It is coincident with the mean velocity of the galaxies inside the cluster (~-374 km/s in comparison to the cD velocity, Hill et al. (1988); Oegerle & Hill (1994). This trend is similar to the kinematics of the Hα gas (van Breugel et al. 1984; Cowie et al. 1983) in the same region, underlining the strong link found between the optical line emitting gas and the cold molecular gas. The gas at ~-350 km/s is concentrated at the North-West from the galaxy, but seems also extended towards the cD position (vertical extension on CO(1-0) P-V map). This effect is less visible in CO(2-1), but it might be due to the limited velocity range at 1.3mm. A second behavior clearly seen in CO(2-1) is a velocity gradient from the NW peak at ~-350 km/s to the galaxy position at ~0 km/s. This trend is also visible, even if fainter in the CO(1-0) line.

5. **Discussion**

5.1. *Cold ICM Gas*

The first question that must be adressed is whether the cold molecular gas we observed is a cluster phenomenon or whether it is associated with the central cD galaxy. We noticed that the cold gas is not centered on the galaxy

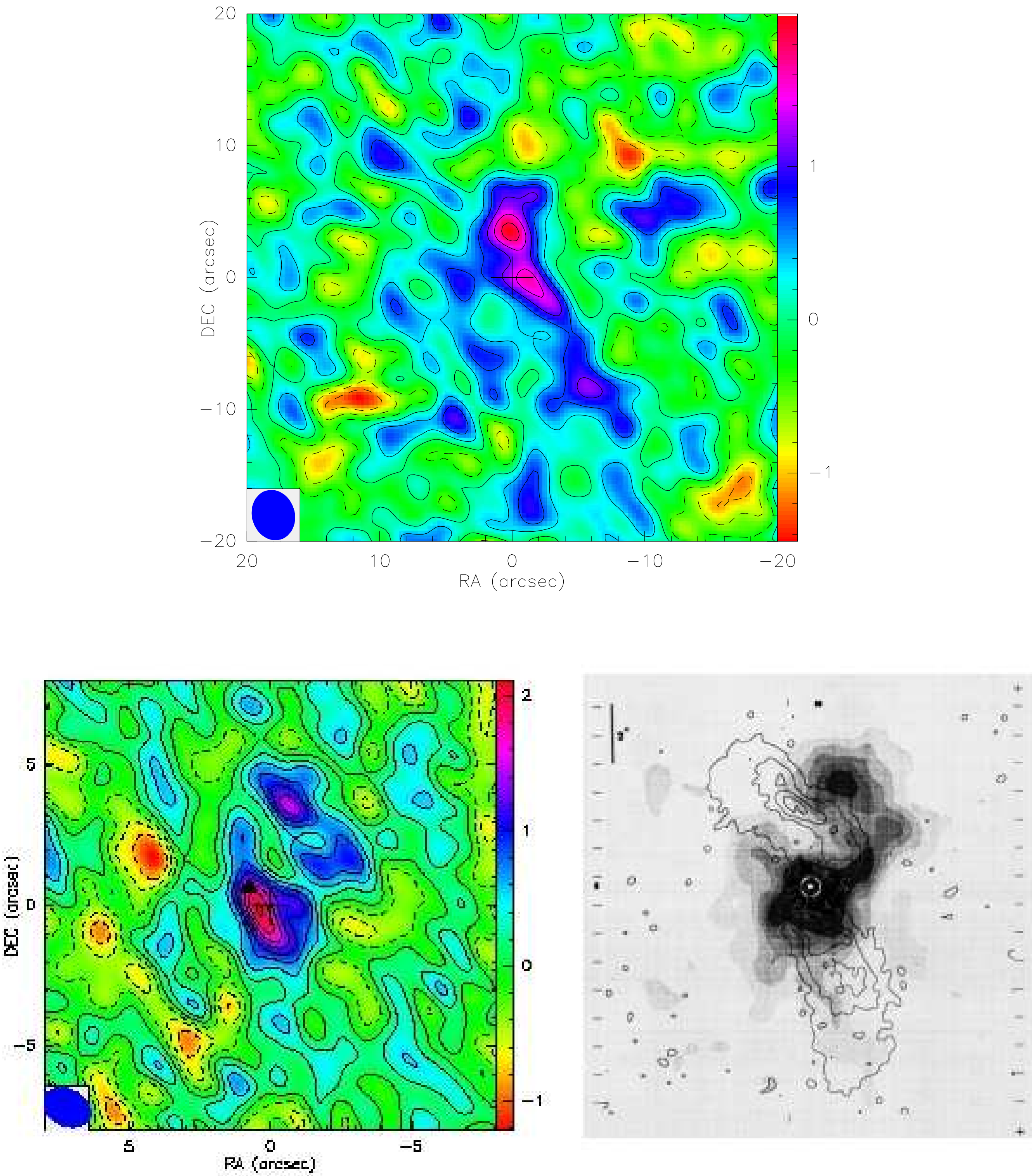

FIG. 1.— Top: C0(1-0) integrated emission. Linear contours are drawn from -3σ to 6σ, spaced by $1\sigma = 0.36$ Jy/beam·km/s. Dashed are negative contours. The beam is plotted in the bottom left corner. Bottom left: CO(2-1) integrated map. Contours are from -3σ to 8σ, spaced by $1\sigma = 0.26$Jy/beam·km/s. The black triangle indicates the radio source position. Bottom right: Hα + [NII] line emission in greyscale, overlaid with the 6cm continuum emission from 4C+26.42 radio lobes (van Breugel et al. 1984).

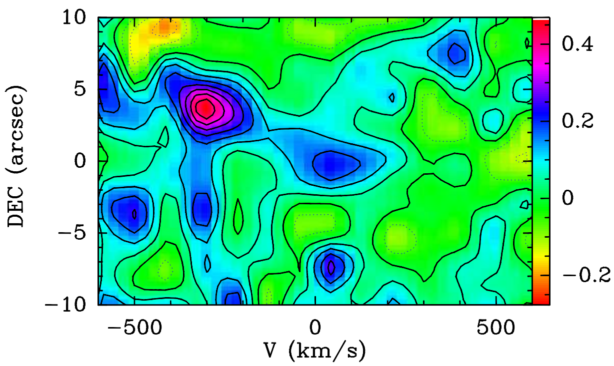

FIG. 2.— Position-Velocity diagram in CO(1-0) emission line. The positions are along a slit of 5″ width (integrated), centered on the galaxy position and aligned with the maximum of emission ($PA = 27°$).

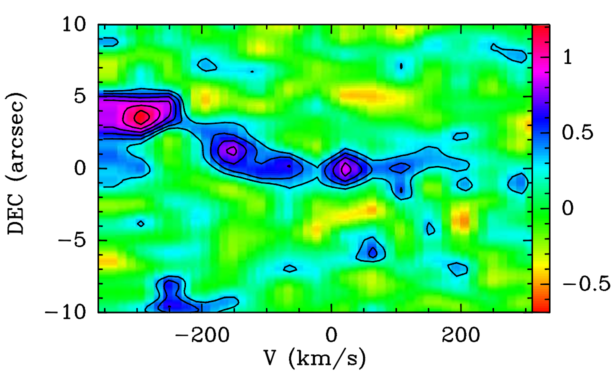

FIG. 3.— Position-velocity map in CO(2-1) emission line in the same region as in Fig. 2.

position but along the NW lobe edge. Its kinematics do not reveal a rotating disk of gas around the cD. So the cold gas is unlikely to come from the cD.

The CO emission is found to be correlated to the Hα luminosity in several clusters of galaxies with cooling flows (Edge 2001; Salomé & Combes 2003). The optical filamentary emission origin is still debated, but is certainly a cluster phenomenon. The outstanding association of the morphology/dynamics of the optical nebulosities and of the molecular gas in Abell 1795 suggests an intracluster origin of the cold gas and confirms that Hα is probably the best tracer of CO emission in cooling flow clusters of galaxies.

The fact that cold gas emission is extended and homogeneous also argues for a cluster phenomenon, corresponding to the cooling of the hot X-ray gas.

5.2. *Two Identified Cooling Regions*

A cooling flow scenario associated with accretion of cooled gas by the cD galaxy may explain the similar velocity behaviour of the gas seen through optical and millimetric wavelengths (taking into account the peculiar velocity of the central galaxy in the cluster core). The gas in the outer part of the flow (NW) is at the mean cluster velocity, and it may be a residual of gas cooling within the cluster potential. The gas in the vicinity of the cD has a velocity close to that of the cD. The velocity gradient clearly seen through CO(2-1) reinforces this interpretation (see Fig. 2 and 3). We may have seen the cold component in a steady state cooling flow, which deposits cooled gas in the ICM and also fuels the activity of the central galaxy nucleus.

5.3. *Radio Jet–Cooling Gas Interaction*

The cold gas is interacting with the central galaxy, its local potential and the radio lobes emerging from 4C+26.42. The shell-like geometry of the cold molecular gas is very interesting. The radio lobes seem to avoid the presence of CO emission. Cavities have been recently imaged in X-rays in several clusters of galaxies, raising the question of the interaction of the hot cooling ICM with the central radio source activity (Brüggen & Kaiser 2002; De Young 2003).

In particular, in Abell 1795, the X-ray peak is not coincident with the cD position, but slightly North-West, along the lobe, coincident with the NW cold gas region. Since the radio source is embedded in a hot cooling gas, the lobe expansion may have pushed the surrounding gas, accelerating and compressing the dense X-ray core. As the cD is not at rest, the central galaxy motion in the ICM may also have distorted the northern lobe until the ram pressure is balanced by the internal pressure of the radio plasma. For a a cD velocity around 400 km/s, the ram pressure is comparable to the thermal pressure deduce from X-ray gas properties by Ettori et al. (2002) in the central 10 kpc. The regions at the edge of the radio lobes that should be denser (with a shorter cooling time) are indeed the location of enhanced optical line emission and of detection of cold molecular emission. Large warm molecular gas, vibrationally excited, is particularly abundant in cooling flows galaxies and in Abell 1795 (Donahue et al. 2000; Wilman et al. 2002). This warm emission could be related to the interaction between jets and molecular gas.

6. **Conclusions**

Cold molecular gas detected in Abell 1795 with the IRAM 30m telescope has been imaged through CO(1-0) and CO(2-1) emission lines in the central 56.5/28.9 kpc with the IRAM Plateau de Bure interferometer. A small fraction of the single dish total flux is retrieved by the actual interferometric observations, supporting an extended homogeneous gas repartition in the center of Abell 1795. The gas imaged is not centered on the cD galaxy. Strong emission is found close to the edge of the NW radio lobe, which confirms that the cold gas detected is certainly from an ICM origin.

In the very central part, the molecular gas morphology is exactly the same as that seen through Hα. It is also coincident with the brightest X-ray emitting region (NW) where the cooling time is the shortest and with the star forming regions along the radio lobes. The AGN and its radio lobes are probably interacting with the cooling gas. The lobes expansion and the cD motion in the ICM may compress the cooling gas, so that the gas cools more efficiently along the radio lobe edges where the cold gas may condense and form stars.

The kinematics confirms this scenario: the cold gas in the vicinity of the cD is at the galaxy velocity and is at the cluster velocity along the NW radio lobe. A velocity gradient from NW towards the cD shows that a part of the gas cooling in the intracluster medium is then accreted by the central galaxy.

More observing time focussed on the 40$''$ North-South filament is now required to search for the cold residual deposited by the flow in the long X-ray, Hα structure.

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