

Mapping the cold molecular gas in a cooling flow cluster: Abell 1795

P. Salomé and F. Combes

LERMA, Observatoire de Paris, 61, Av. de l'Observatoire, 75014 Paris, France

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Abstract. Cold molecular gas is found in several clusters of galaxies (Edge 2001; Salomé & Combes 2003): single dish telescope observations in CO(1–0) and CO(2–1) emission lines have revealed the existence of large amounts of cold gas (up to $\sim 10^{11} M_{\odot}$) in the central region of cooling flow clusters. We present here interferometric observations performed with the IRAM Plateau de Bure interferometer in Abell 1795. Comparison with IRAM 30 m data shows the cold gas detected is extended suggesting a cooling flow origin. The CO features identified are very similar to the structures observed in H_{α} and with the star forming regions observed through UV continuum excess. A large fraction of the cold gas is not centered on the central cD, but located near brightest X-ray emitting regions along the North–West orientated radio lobe. The cold gas kinematics is consistent with the optical nebulosity behaviour in the very central region. It is not in rotation around the central cD: a velocity gradient shows the cold gas might be cooled gas from the intra-cluster medium being accreted by the central galaxy. The optical filaments, aligned with the cD orbit, are intimately related to the radio jets and lobes. The material fueling the star formation certainly comes from the deposited gas, cooling more efficiently along the edge of the radio lobes. Even if some heating mechanisms are present, these millimetric observations show that an effective cooling to very low temperatures indeed occurs and is probably accelerated by the presence of the radio source.

Key words. galaxies: clusters: individual: Abell 1795 – cooling flows – molecular gas

1. Introduction

1.1. Abell 1795

The rich cluster of galaxies Abell 1795 is thought to be the site of a cooling flow, since the temperature measured from X-ray emission is dropping by a factor 3 towards the core, at about 140 kpc from the centre (e.g. Tamura et al. 2001). Fabian et al. (2001) discovered with the Chandra satellite a $40''$ long (~ 60 kpc, with an adopted Hubble constant of $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$) X-ray filament in its core, coinciding with an H_{α} +NII filament previously found by Cowie et al. (1983). This filament is also conspicuous in the U -band (McNamara et al. 1996a), and the site of star formation: the blue continuum along the edges of the radio lobes are resolved into bright knots with the Hubble Space Telescope (HST). The absence of polarized light rules out that the U -band continuum is only due to scattered light from an active nucleus (McNamara et al. 1996b). The cD galaxy, a little South of the Northern peak of the filament, has a positive peculiar velocity with respect to the rest of the cluster galaxies (Oegerle & Hill 1994), and is probably oscillating around the cluster core. The gas filament has a velocity centred on the cluster mean velocity, and may also be sloshing

in the cluster potential (Markevitch et al. 2001). The radiative cooling time of the X-ray emitting gas in the filament is about 3×10^8 yr, quite similar to the dynamical age of the filament (ratio of length to velocity). This supports the cooling flow model, in which the gas is presently cooling from the hot cluster gas. The optical filaments are intimately related to the radio jets and lobes from the radio source 4C+26.42 (van Breugel et al. 1984; Ge & Owen 1993; McNamara et al. 1996). The blue emission is aligned along the edges of the radio lobes, while dust lanes extend along the radio jets and lobes as H_{α} and UV (Pinkney et al. 1996), which might be interpreted as star formation induced by the radio source or the deflection of the radio jets off pre-existing dust and gas. If a burst of star formation were triggered by the expanding radio lobes, the age of the burst population should be $\sim 10^7$ yr. Then, the star formation rate in both lobes, assuming the local IMF, would be $\sim 20 M_{\odot} \text{ yr}^{-1}$, and the stellar mass of the lobes would be $\sim 10^8 M_{\odot}$ (McNamara et al. 1996a). The material fuelling the star formation and the radio source may have two origins: either the cooling flow or gas tidally stripped by galactic interactions (dense molecular clouds are not sensitive to ram pressure). The morphology and kinematics of CO emission could distinguish between the two possibilities.

Send offprint requests to: P. Salomé,
e-mail: philippe.salome@bspm.fr

1.2. Cold molecular gas

Previous spatially resolved CO emission in a cooling flow cluster has already been reported in the Perseus galaxy NGC 1275, with a morphology related to H_α and X-ray (e.g. Inoue et al. 1996, Bridges & Irwin 1998, using the Nobeyama Millimeter Array and the IRAM 30 m single dish telescope respectively). However, this galaxy is also the result of a merger, the CO is observed in the center in rotation around the AGN, and the origin of the CO gas is multiple, including the cooling flow. The picture appears clearer in Abell 1795. Recent OVRO observations, (Edge & Frayer 2003) observed CO emission in a compact region centered on the central galaxy in five cooling clusters (Abell 1068, RX J0821+07, Zw 3146, Abell 1835 and RX J0338+09).

The core of the Abell 1795 has also been observed in the CO rotational line emission, tracing the cold molecular hydrogen. The total emission was first detected with the IRAM 30 m telescope (Salomé & Combes 2003) and the mass of the cold gas in a region of $23''$ was estimated to be $4.8 \times 10^9 M_\odot$. It is likely to be a lower limit, since the measured metallicity of the Intra-Cluster Medium (ICM) is 0.2–0.3 solar (Tamura et al. 2001). And much more gas might be present into the cooling radius. The molecular mass would then be much larger, by an order of magnitude, than in a typical cD galaxy. The mass deposition rates deduced from recent Chandra X-ray observation of Abell 1795 are $\sim 7.9 M_\odot \text{yr}^{-1}$ in the central region covered by the 30 m telescope beam of $22''$ (while it is $\sim 100 M_\odot \text{yr}^{-1}$ within 200 kpc, Ettori et al. 2002), therefore compatible with our detection of cold molecular gas. The cold gas detected might have been deposited out of the flow in ~ 600 Myr. The cooling time of the hot X-ray gas is around ~ 300 Myr in the same region. In a steady state cooling flow scenario, a steady reservoir of cold gas with a mass close to the mass deduced from CO observations is possible since the star formation rate (Smith et al. 1997; McNamara et al. 1996b) is close to the mass deposition rate. However, the lack of spatial resolution prevented to conclude that the cold gas was associated to the cooling flow, since it could have been interstellar gas rotating in the central cD galaxy. The gas detected here through CO rotational lines is cold (about 20 K). The intensity ratio between the CO(1–0) and CO(2–1) (obtained with the IRAM-30 m, Salomé & Combes 2003) is consistent with an optically thick gas. Warm H_2 , vibrationally excited, is particularly abundant in cooling flow galaxies and in Abell 1795 (Donahue et al. 2000; Wilman et al. 2002). The warm H_2 emission could be related to the interaction between the jets and the cold molecular gas.

2. Interferometric observations

The observations we present here, have been done with the IRAM interferometer in winter 2003, with $3.2''$ and $1.8''$ spatial resolution at the CO(1–0) and CO(2–1) lines respectively. The frequencies were centred at 108.413 and 216.822 GHz, corresponding to the redshift $z = 0.06326$ of the cluster cD galaxy hosting the 4C+26.42 radio source. The velocity of the cD is redshifted by 374 km s^{-1} with respect to the mean velocity of

the galaxies inside 200 kpc (Hill et al. 1988; Oegerle & Hill 1994). The total integration time is 43 h, in C and D configuration, with 5 or 6 antennas. To improve the signal-to-noise ratio, we smoothed the spectral resolution to channels of 88 km s^{-1} at CO(1–0) and 44 km s^{-1} at CO(2–1), since the width of the line is expected to be large ($\sim 500 \text{ km s}^{-1}$) from the 30 m observations. The signal-to-noise ratio is slightly better in the CO(2–1) map, and the higher spatial resolution allows to better identify the H_α /CO correspondance; however, the primary beam ($FWHP = 22''$) is twice smaller than in CO(1–0) ($FWHP = 45''$), preventing to observe the spatial extension of the filaments.

3. Results

3.1. The molecular gas morphology

The resulting integrated maps in the two CO lines are shown in Fig. 1. At 3 mm, we detect a continuum source, at the position of 4C+26.42, of 7 mJy. This source is the expected continuation of the synchrotron emission detected at lower frequency, with a flux decreasing slope of $\alpha = -0.98$. The CO(1–0) map shows the emission found, once the continuum has been subtracted. We clearly detect CO emission associated with the cooling region already detected in X-rays, U -band excess and H_α . The maximum of the emission is located in two main regions: one coincident with the maximum of X-ray emission and occurs at the North–West of the cD, the other is at the galaxy position and extending to the South. The CO emission is too faint to be compared to the large North–South orientated filamentary structure seen in X-ray and H_α . Nevertheless, in the very central part, the cold gas morphology is very similar to the H_α and Blue continuum structures identified by van Breugel et al. (1984), McNamara & OConnell (1993), Smith et al. (1997) as shown in Fig. 1. The H_α -CO correlation has been found for global emission statistically over the CO-detected cooling flows (Edge 2001; Salomé & Combes 2003), and it is now confirmed by their coinciding morphologies in A 1795.

3.2. The molecular gas kinematics

The kinematics of the molecular gas in A1795 is shown in Figs. 2 and 3. We present position-velocity diagrams for the two CO lines along the axis of maximum emission ($PA = 27^\circ$) through the centre of the cD galaxy. There are two separated trends in velocity in both the CO(1–0) and CO(2–1) lines. One is centered on the galaxy position at zero velocity. The other is $5''$ North–West from the radio source position and is at $-300/350 \text{ km s}^{-1}$ relative to the galaxy velocity. There is also a regular gradient from the galaxy centre towards the North–West ($5''$). The velocities measured in the CO brightest regions are coinciding with those in H_α , by van Breugel et al. (1984) and Anton (1993), supporting the association between the cold gas and the hot gas/optical structures. The peak of H_α emission does not follow the peculiar velocity of the cD galaxy in the cluster, but is centred on the cluster mean velocity (-350 km s^{-1}), i.e. the mean velocity of the galaxies inside 200 kpc, while it reaches the cD velocity at the galaxy position.

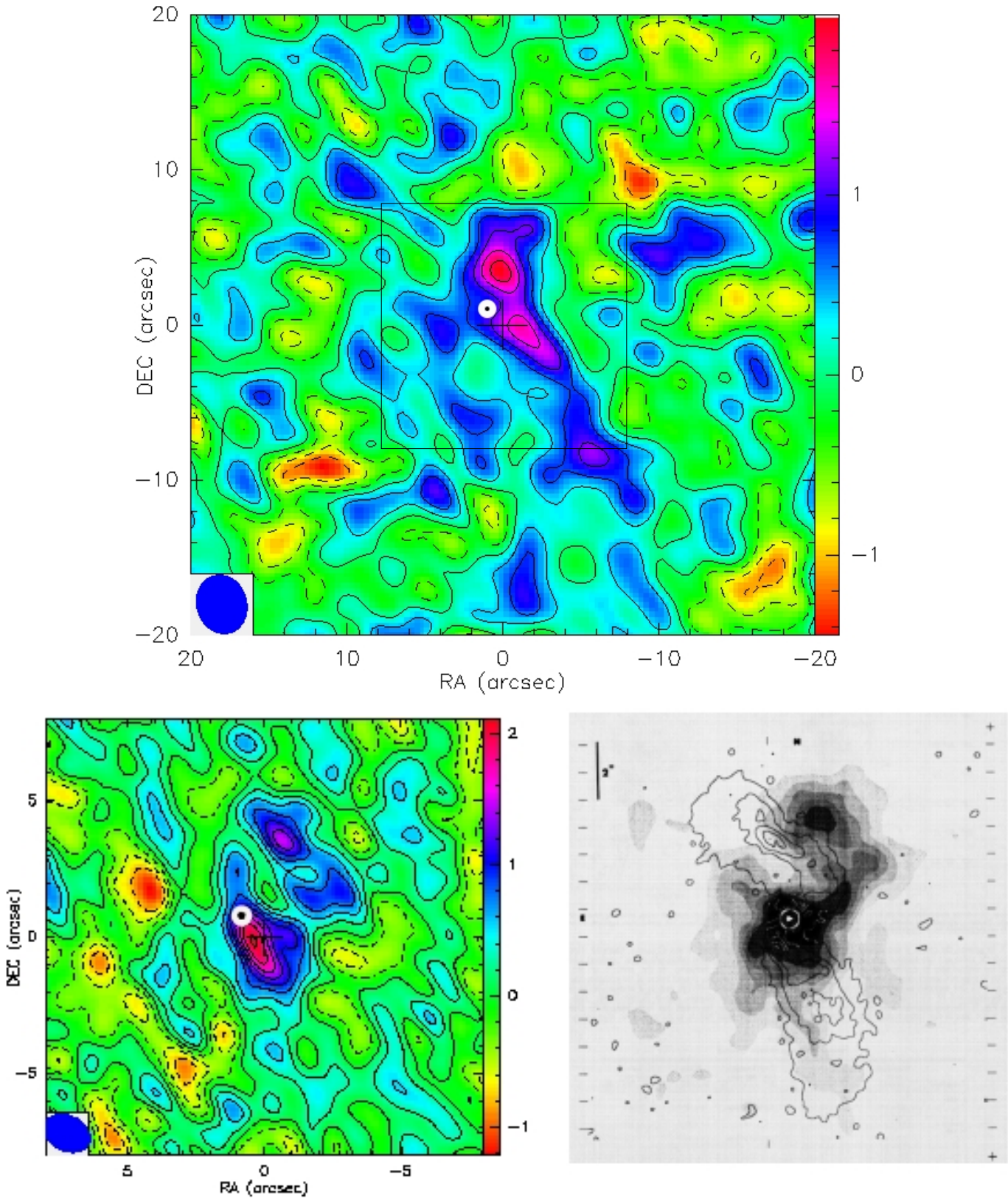


Fig. 1. *Top:* CO(1–0) integrated emission. Linear contours are drawn from -3σ to 6σ spaced by $1\sigma = 0.36 \text{ Jy beam}^{-1} \text{ km s}^{-1}$. Dashed are negative contours. The beam is plotted in the bottom left corner. The black box indicate the size of the CO(2–1) integrated map presented in the bottom left. Contours are from -3σ to 8σ spaced by $1\sigma = 0.26 \text{ Jy beam}^{-1} \text{ km s}^{-1}$. The white disk indicate the radio source position. *Bottom right:* H α + [NII] line emission in grey scale, overlaid the 6 cm continuum emission from 4C+26.42 radio lobes (van Breugel et al. 1984).

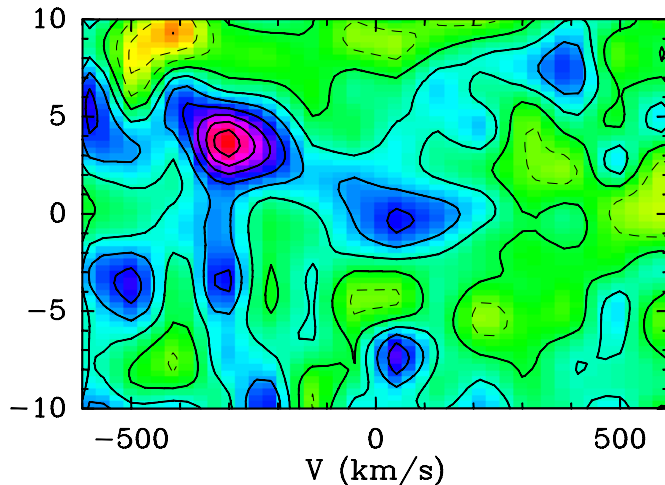


Fig. 2. Position-velocity diagram in CO(1–0) emission line, the positions are along a slit of 5'' width (integrated), centered on the galaxy position and aligned with the maximum of emission (PA = 27).

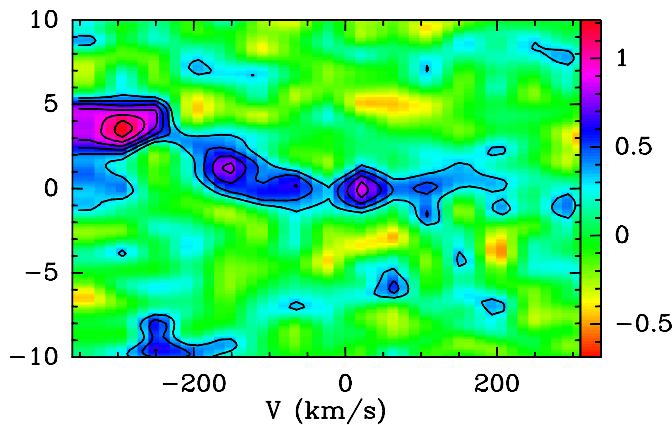


Fig. 3. Position-velocity map in CO(2–1) emission line in the same region as in Fig. 2.

The kinematics of the cold gas and the H_α line emitting gas is compatible with the cooling flow scenario. At the North–West position, coincident with the brightest X-ray region, the gas is cooling within the cluster potential. Near the cD, the flow is captured by the cD potential (and the inner gas have a velocity close to that of the galaxy, with a wider range of velocities).

4. Discussion

The peculiar morphology of the cooling gas (X-ray, H_α , blue continuum, molecular gas) appears to avoid the radio lobes, particularly visible in the north (Fig. 1). This can be interpreted as the radio jet heating and displacing the hot X-ray gas as it cools on the cD. This scenario is supported by the detection of X-ray cavities coincident with radio lobes in an increasing number of cooling flow clusters imaged by the recent high spatial resolution X-ray satellite Chandra (Böhringer et al. 1993; Fabian et al. 2000). The cold molecular gas will condense more efficiently in the resulting cold front surrounding the cavities. This is also in these fronts that stars are formed, explaining the optical blue continuum. The CO emission is not associated

to the nearby galaxies of the cluster. It cannot be all tidally stripped gas, since most of the molecular gas detected is not centered on the galaxy, see Figs. 2 and 3. The association of the CO emission with the cavity border supports its origin in an intermittent cooling flow scenario, where the gas cooling more rapidly along the radio lobes is then accreted by the central galaxy and can fuel the central AGN activity, which may regulate the cooling. Finally, an important result of these interferometric observations is that the total flux retrieved is only 25% of the single dish flux obtained previously with the IRAM 30 m telescope: this means that most of the emission is extended with respect to the 45'' beam (corresponding to 65 kpc), which argues for a cooling flow origin of the cold gas at larger radii.

5. Conclusions

Through interferometric mapping of the CO emission, we have shown that the cold molecular gas is associated to the cooling flow in Abell 1795. The CO emission is closely associated to H_α and to X-ray emissions, and is concentrated at the boundaries of the bubbles or cavities created by the central AGN. Cooling occurs preferentially at the edge of these cavities, where the hot gas is denser. The peculiar long filament morphology of the cooling gas in A 1795, and its kinematics, are best interpreted as a cooling wake (Fabian et al. 2001): the cD galaxy oscillates in a few 10^8 yr period, and during a cooling time the large-scale hot gas sees the minimum of the potential roughly as a straight line along the cD orbit. The AGN in the cD core and its plasma jets certainly provide a feedback heating, seen as cavities in the X-ray maps, coincident with the radio-lobes, but is also probably increasing the cooling to very low temperature along the edges of these cavities, where the cold gas condenses and forms stars. A velocity gradient of the cold gas is revealed, that shows it is falling on the central galaxy and may provide the AGN fueling material which is consistent with an AGN regulated cooling flow scenario.

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