Hunt for Molecules
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SEARCH FOR MOLECULES IN COOLING FLOW CLUSTERS OF GALAXIES

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Abstract. X-ray observations of the hot intra-cluster medium predict that the diffuse gas is cooling down toward a central object, in general a cD galaxy. No direct evidence of any cooling flow exists yet. XMM-Newton spectra even stressed the lack of gas at a temperature below of 1/3 T_{vir}, as expected in the core of cooling flow clusters. We present here a complementary approach : we searched for cooled residual gas in the millimeter wavelengths. The detection of molecular gas and the first maps of CO(1-0) and CO(2-1) line emission around central cluster cD galaxies are presented here. The molecular emission in these objects is peculiar and suggests a possible association with a cooling flow. These results open a new area for the study of the interaction of the ICM with galaxies. Several projects are in progress in the millimeter domain to use the molecular emissions as a probe of the still puzzling problem of cooling cores. We present some of them before discussing the impact of future new facilities for millimeter observations of cold cores in clusters of galaxies.

1 Introduction

X-ray data suggest the existence of large cooling flows in rich galaxy clusters. The satellites Chandra and XMM-Newton confirmed that the hot X-ray gas,

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pervading the cluster, cools and condenses toward the centre (usually a cD galaxy) but also raised many new questions, as for instance the necessity of re-heating phenomena. The previously overestimated mass deposition rates were re-evaluated and the expected cold residual gas cooling out of the X-ray band now reaches values consistent with the mass derived from recent CO observations. The cold cores that we have detected are consistent with an intermittent cooling flow scenario. As suggested by Bohringer et al. (1993), the presence of a central AGN heating source, hosted by the central galaxy and fueled by the cooling flow, may regulate the cooling in a self-regulated cycle.

The central galaxy in cooling flow clusters is frequently surrounded by a large H_α filamentary nebulosity, see Conselice et al. (2001) for example. The origin of these optical filaments and their ionization source are not identified yet. However they do trace, in some part, the radiative cooling of the hot intracluster medium but also the presence of star forming regions necessarily fueled by some cold molecular reservoir.

2 The long search for the cold fate of the cooling gas

2.1 First detections

Cold molecular gas has been detected in several cooling flow clusters of galaxies with the IRAM 30m telescope, the JCMT and the CSO for the very first time (Edge 2001, Salomé & Combes 2003). However the origin of this gas is still controversial. A summary of some of these detections characteristics is presented in Tab.1.

A clear association of the molecular gas with the H_α filamentary nebulosities is pointed out. The cold gas masses deduced here are in good agreement with the predictions of X-ray mass deposition rates.

2.2 Origin of the gas

The dynamics of the molecular gas show that the emission lines are not centered at the galaxy redshift. This suggests a perturbed gas interacting with its environment. The amounts of cold gas detected are quite large and part of it could come from a cooling flow. Nevertheless, this gas can also partly belong to the central cD galaxy or be some gas tidally stripped from a close companion crossing the cluster centre. To investigate the different

Sources	lines CO	Peak (mK)	Position (km/s)	M_{H_2} ($10^8 M_\odot$)
A262	1-0	2.9	31±24	2.3±0.3
PKS0745-191	1-0	2.0	18±29	40±9
	2-1	11.2	-45±15	
RXJ0821+07	1-0	8.9	268±8	130±20
	2-1	9.9	275±34	
A1068	1-0	10.1	-45±4	420±20
A1795	1-0	3.4	-190±28	48±6
	2-1	6.1	-128±31	
Zw8193	1-0	2.1	14±20	150±30
A496	1-0	1.5	382±39	4.3±1.0
	2-1	3.0	114±29	
A646	1-0	1.5	105±39	79±2
	2-1	1.9	46±54	
A780	1-0	1.8	219±31	20±3
A2657	1-0	3.0	147±13	2.9±0.1

Table 1. Cold molecular properties of cooling flows clusters detected with the IRAM 30m telescope (Salomé & Combes, 2003). The line position is determined by comparison to the central galaxies rest frame.

the cold molecular gas origins, we mapped 3 cluster cores at millimeter wavelengths.

3 Mapping the molecular gas

The maps presented here have been obtained with the IRAM Plateau de Bure interferometer. The emission lines detected with the 30m telescope were very faint : a few mK. So large amounts of telescope time, involving observations at the limit of the interferometer capabilities, have been invested during the past three years to get those results.

3.1 Abell 1795

The CO(1-0) map of Fig. 1 is a mosaic of merged data from Salomé & Combes (2004) and recent data. It is possible to see the extended CO emission, far away from the galaxy center, along a filamentary structure also seen through H_α (Salomé & Combes 2006, in prep).

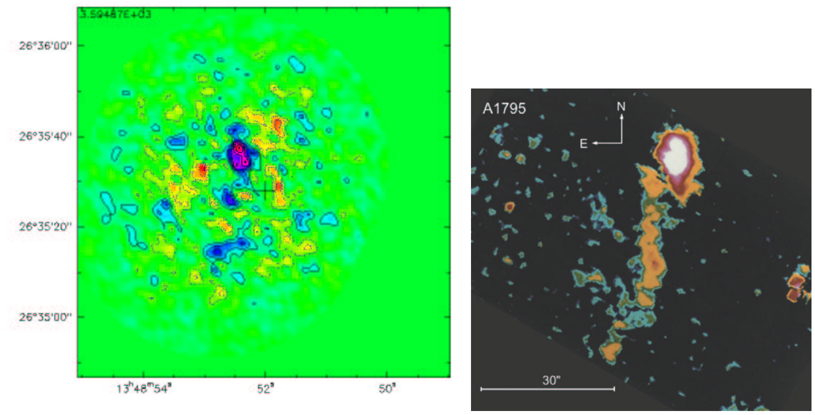

Fig. 1. Left: Integrated emission in CO(1-0) over the whole map. Contours are spaced by one sigma. Right: H_α image same scale, by Cowie et al. (1985)

3.2 RXJ 0821+07

RXJ 0821+07 is one of the brightest CO detection. The molecular gas is associated neither spatially nor dynamically with the central galaxy. Here again there is rather a clear morphological association of the molecular emission with filamentary H_α emission (Salomé & Combes 2006, in prep).

3.3 NGC 1275

This galaxy, at the center of the Perseus cluster has been observed with HERA (Salomé, Combes, Edge et al. 2006, submitted). For the first time very large filamentary CO(2-1) structures begin to be visible far away from the central cD. Moreover, two components are identified : a narrow component roughly centered on the galaxy redshift superposed on a broad line

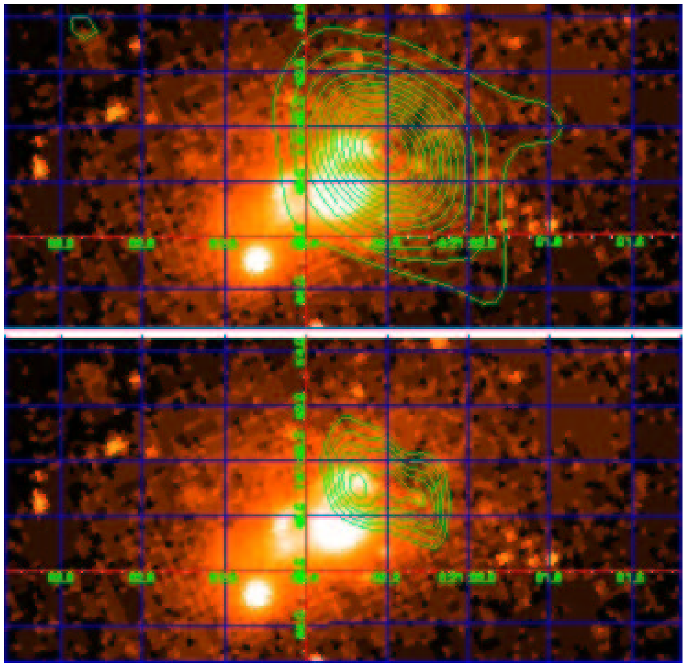

Fig. 2. RXJ 0821+07: 20.5 $\times$ 16" HST image of the cluster core, the galaxy is at the center of the field (Bayer-Kim et al. 2002). Contours show the molecular gas integrated line emissions. Top : CO(1-0), rms = 0.28 Jy/beam.km/s. Bottom, CO(2-1), rms = 0.56 Jy/beam.km/s. Levels are spaced by 1σ.

emission roughly centered on the cluster redshift. No rotation pattern has been identified.

These last observations confirm that the molecular gas is perturbed. It may be gas cooling down along filaments toward the central cD galaxy before being gravitationally attracted. It is also possible that some of the X-ray gas has been pushed by the expansion of the radio lobes in the ICM. Some cooler gas may then have been dragged out and be in a cooling process at larger radius than expected.

In NGC 1275, like in Abell 1795, we have found that the cold molecular gas is located along the edges of the radio lobes, where the X-ray emission

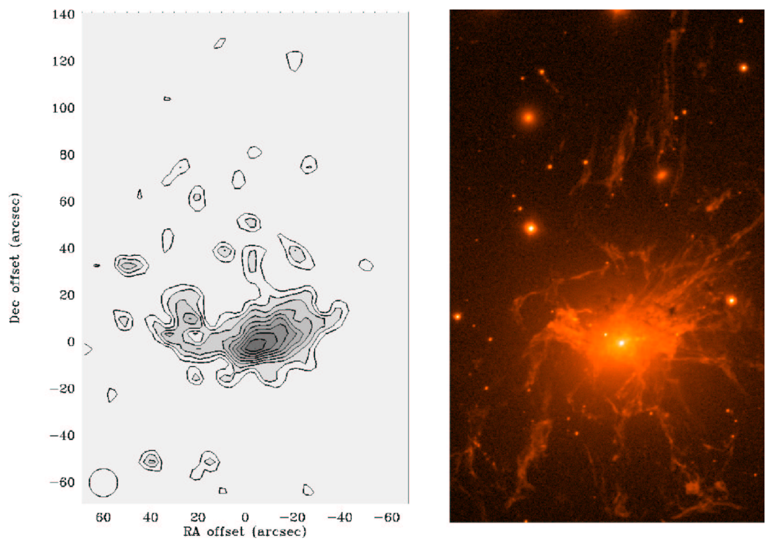

Fig. 3. NGC1275. Left: Integrated CO(2-1) emission over the whole map. The region covered by the HERA observations is a central 138x138" map, with a northern 66x66" addition centered in (0,108") to cover the vertical northern filaments. Contours are linear, form 10 to 100% of the maximum emission of 8.3 K km/s, in T_A^* scale. The 12″ beam is indicated at the bottom left. Right: H_α image at the same scale, by Conselice et al. (2001)

is enhanced. The hot ICM could have been compressed and cooled down more rapidly in this region where star formation is also pointed out (Mc Namara et al. 1996).

4 Perspectives

4.1 Search for other molecules

We have searched for tracers of dense molecular clouds. Table 2 shows the lines that we searched for with the IRAM 30m telescope. No clear detections were possible with the actual instrument capabilities (Edge, Wilman, Salomé 2006, in prep.).

Cluster	Date	Line	Freq (GHz)	Tsys	time[1]
Abell 1068	28/07/04	HCN(1-0)	77.8469	156	102
Abell 1068	31/07/04	HCN(1-0)	77.8469	175	96
Abell 1068	30/07/04	HNC(1-0)	79.6314	144	96
RXJ0821+07	29/07/04	HCN(1-0)	79.7810	155	120
RXJ0821+07	30/07/04	HCN(1-0)	79.7810	151	36
RXJ0821+07	31/07/04	HNC(1-0)	81.6098	169	54
NGC4104	30/07/04	CN(1-0)	110.3780	169	54
NGC4104	30/07/04	CN(2-1)	220.6526	203	54
NGC4104	31/07/04	CN(1-0)	110.3780	186	72
NGC4104	31/07/04	CN(2-1)	220.6526	445	72

Table 2. Search for dense gas tracers in cooling flow clusters.

4.2 Gas to dust ratio

Continuum observations of dust emission are in progress with MAMBO2, the bolometer installed on the 30m telescope. The time to destroy dust grains by sputtering is very short in this X-ray environment. Estimates of gas to dust ratio would thus help to constrain the origin of the gas and the molecules formation scenario. The major problem we face here is the continuum AGN emission that can pollute the very faint signal we are interested in. Multi-wavelengths observations in the mm and FIR have to be engaged to evaluate the dust temperature and disentangle the different continuum emission processes.

4.3 Radio lobes cavities

We also investigated the intermittent cooling flow scenario by observing several cooling flow clusters which present X-ray holes at the position of radio lobes. We searched for CO(1-0) and CO(2-1) emission lines along the radio edges of those clusters. These observations are in progress now and will help to understand the complex cooling mechanisms in clusters cores.

4.4 Future facilities

The higher spatial resolution of the new generation Plateau de Bure interferometer, and the increased sensitivity of the new receivers will enable to go deeper in the mapping of X-ray identified cooling cores before ALMA first science.

Indeed, ALMA will be the perfect instrument to study statistically the cooling flow problem through the millimeter. It will be possible to map simultaneously several molecules for each cluster and to study the physics of molecular clouds in such complex environments. The large number of observable clusters will allow to probe the evolutionary processes of cold gas accretion on galaxy (central cD, elliptical galaxies) and to constrain the galaxy formation models.

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