Observations of CO in the eastern filaments of NGC 1275

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ABSTRACT

We recently found extended CO(2–1) emission from cold molecular gas embedded in the network of H α filaments surrounding the galaxy NGC 1275 (Salomé et al. 2006). We now present CO(2–1) interferometer maps of the eastern filaments, at high spatial and spectral resolutions. The cold molecular gas is detected by the Plateau de Bure Interferometer along the eastern filaments over an extent of 15'', or with a projected length of 5 kpc. In our 2.5'' beam, the main CO filament is mostly unresolved along its minor axis. The multiple peaks along the CO filaments and the low values of the observed CO brightness temperatures imply further unresolved structures that may be giant molecular clouds. These clouds have very narrow line-width emission lines (~ 30 km s⁻¹). The CO emission is optically thick. It very likely traces cold clouds bound under their own self-gravity that may be falling back in the gravitational potential well of the galaxy. Such a picture would agree with current models of “positive feedback” in which some of the hot gas around NGC 1275 (a) is trapped by buoyantly rising bubbles inflated by the energy input of the 3C 84 AGN, (b) subsequently cools efficiently at a larger radius around the edges of the hot bubbles, and (c) then falls back in self-gravitating clouds of molecular gas toward the center of the galaxy.

Key words. galaxies: cooling flows – galaxies: individual: NGC 1275 – galaxies: ISM – galaxies: intergalactic medium – galaxies: kinematics and dynamics

1. Introduction

The galaxy NGC 1275 lies at the center of the Perseus cluster, the brightest galaxy cluster in the sky in X-rays. Its surface brightness follows a $r^{-1/4}$ law with an effective radius of 15 kpc. This starlight dominates over the light of the Perseus cluster right up to the Holmberg radius of NGC 1275 of 122 kpc. Beyond this distance, the cD envelope of NGC 1275 continues out to a cut-off radius of 250 kpc (Oemler 1976; Schombert 1987; Rebusco et al. 2005¹). The galaxy has a remarkable system of H α filaments with a broad range of gas temperatures and densities (e.g., Crawford et al. 1999; Conselice et al. 2001). The filaments are very luminous (4×10^{42} erg s⁻¹ in H α and [NII]; Heckman et al. 1989), but the gas excitation mechanism is still a matter of debate. The filaments do not contain many young star clusters to ionize the gas; a constant source of heating could be present that produces their low-excitation spectra, but AGN-heating of the filaments has been ruled out. Hot (2000 K) molecular gas is also detected in the filament system in the H₂ ro-vibrational lines at 2 μ m (e.g., Hatch et al. 2005), and cooler (200 K) molecular gas is detected in the mid-IR H₂ rotational lines (Johnstone et al. 2007). Evidence for possibly even colder (10 to 100 K) molecular gas has recently been found in the filaments in CO (Salomé et al. 2006, 2008; Lim et al. 2008). The origin of the filaments is unknown; they may be related to the cooling of uplifted gas. A currently popular scenario is that the supermassive black hole 3C 84 emits radio jets surrounded by broad envelopes of

entrained, hot, fast-moving but non-relativistic plasma, that pushes and compresses the surrounding gas within the “isothermal” core of NGC 1275. The resulting bubbles then expand in the surrounding gas and rise higher in the central galaxy’s potential well (for recent model simulations see, e.g., Brüggén & Kaiser 2002; Churazov et al. 2000; Soker & Pizzolato 2005; Reynolds et al. 2005; Revaz et al. 2008; Mathews & Brighenti 2008; Sutherland & Bicknell 2007; Vernaleo & Reynolds 2007). Some of the lower-temperature, higher-density ambient medium is carried by the outward moving bubbles and slowly cools at greater radius. The further decrease of its pressure and the increase of its density lead to runaway cooling instabilities that generate long filamentary structures. The cooled gas falls back down in the potential well of the central galaxy, on a time scale of 10⁸ years (Revaz et al. 2008). If the cooling gas is able to condense into giant molecular clouds, they should be able to form new star clusters on their way back in. In NGC 1275, the H α kinematics support this scenario: the measured velocity along the filaments change sign in the middle, and Hatch et al. (2006) deduce that the gas is inflowing at the base, while outflowing at the top, with an interruption in the middle coinciding with an X-ray shock and a ghost bubble.

This paper presents CO(2–1) images of the eastern filaments located at a projected distance of 8 kpc from the center of NGC 1275. Sections 2 and 3 report the high spatial and spectral resolution observations of the molecular gas morphology and kinematics. Section 4 compares these results with bubble models, and Sect. 5 discusses possible explanations for the origin of the cold gas in the filaments.

¹ All radii are re-scaled with $H_0 = 71$ km s⁻¹ Mpc⁻¹.

2. Observations

To investigate in more detail the structure of the cool molecular gas associated with the H α filament system of NGC 1275, we made new CO(2–1) observations of the prominent eastern filament located at $(\Delta\alpha, \Delta\delta) = (+20'', +10'')$ from the radio source 3C 84 at the galaxy's center. We used the IRAM Plateau de Bure Interferometer with 6 antennas in the most compact configuration, which gave beams of $2.5'' \times 2.4''$ (natural weighting) and $2.2'' \times 2.0''$ (robust weighting). The receivers observed the H and V polarizations simultaneously at 226.559 GHz, which is equal to the rest frequency of the CO(2–1) line divided by $(1 + z_{\text{lsr}})$, where we took $z_{\text{lsr}} = 0.01756$, as the reference redshift for the CO in the center of NGC 1275. All velocity offsets in the figures are relative to this frequency. The SSB system temperatures were ~ 220 K at 1.3 mm. The 1 GHz-wide IF band covered a velocity range of 1354 km s^{-1} , and was observed with a channel spacing of 2.5 MHz. Fluxes were calibrated with MWC349 and reference quasars. The total on-source integration time with 6 antenna was 6.4^{h} . Amplitudes and phases were calibrated with 3C 84 whose flux density was 4.3 Jy at 1.3 mm. During the observations, the antennas were pointed toward the eastern filament, and the position offsets in the figures are relative to a (0, 0) position of $03^{\text{h}}19^{\text{m}}50.0^{\text{s}}, +41^{\circ}30'47.0''$ (J2000), centered on this filament. Because 3C 84 was a full primary beamwidth ($22''$) away from this position, its apparent flux was attenuated to 97 mJy on our maps, thereby reducing the effect of beam sidelobe responses to this strong continuum source.

3. Filament-like structure in the CO

3.1. Overall morphology of the CO filaments

Figure 2 shows the mean CO(2–1) intensity in the east filament region, and the moment map of isovelocity contours. The molecular gas is in an elongated structure that coincides with the H α filaments (see e.g., the H α images by Conselice et al. 2001). All the CO(2–1) flux found with the 30 m telescope in the eastern filament region is detected by the interferometer: 40 Jy km s^{-1} . This means that *all the molecular gas in the interferometer field of view is in this elongated structure – no further extended emission exists* that has been lost by missing short spacings of the interferometer. Much more cold molecular gas is present within the central 2-kpc radius, as is shown by the spectrum of CO emission on the position of 3C 84 (Fig. 3, region D; see Salomé et al. 2008, for details).

Figure 3 presents position-velocity diagrams along the main filament's major axis (PA 70°), and along its minor axis (PA -20°). Region B is at -70 km s^{-1} with a hint of a velocity gradient. Region A also peaks at -70 km s^{-1} . Region C is resolved in 3 substructures with a clear velocity change from -160 km s^{-1} at offset $-6''$ to -100 km s^{-1} at offset $-2''$ and then to -40 km s^{-1} at offset $0''$. The velocity change of 120 km s^{-1} over a projected extent of $6''$, or 2.1 kpc, gives an apparent gradient in the plane of the sky of the line-of-sight velocity of $0.06 \text{ km s}^{-1} \text{ pc}^{-1}$. The $p-v$ diagrams parallel to the minor axis Fig. 2, panels 3 and 4) show no clear velocity gradient. Regions A, B and C may simply be three separate structures. The CO filaments are seen projected on the plane of the sky, and they are likely to be made of different sub-filaments, as in the H α images.

The interferometer maps show several substructures inside the filaments. We merged the new interferometer data with our previous CO(2–1) observations at the IRAM 30 m telescope

(Salomé et al. 2006) that covered a much larger field of view, in order to improve the cleaning algorithm. Figure 1 shows the merged single-dish+interferometer map, with insets of five spectra at the CO peaks in the filaments. The CO(2–1) lines in the filaments are narrow ($\leq 100 \text{ km s}^{-1}$). The mean velocity of the CO is shifted by about -100 km s^{-1} relative to the midpoint of the CO(2–1) line at the center of NGC 1275, which is at a velocity offset of -30 km s^{-1} , and is also much broader ($\text{FWHP} \sim 300 \text{ km s}^{-1}$) than the CO lines in the filaments. The peak of the central CO emission is 7 to 10 times the CO peak intensity in the brightest components of the eastern filament system.

All the filament regions labeled A, B, and C are elongated. The long axes are resolved by the interferometer, while the apparent minor axes are close to the beam size, indicating they are unresolved, with sizes $< 1.5''$ ($< 500 \text{ pc}$). The apparent (beam-smoothed) sizes for region A are $7'' \times 3''$, for region B, $7'' \times 3''$, and for region C, $10'' \times 3''$. Regions A and C are aligned on the same H α filament, while region B lies on a separate H α filament, $5''$ north of A–C. These filaments are projected on the plane of the sky, so the minimum length of the region C major axis in CO is 3.5 kpc. If regions A and C are two substructures of the same CO filament, then its projected length could be as much as 6 kpc.

3.2. Are the CO clumps complexes of GMCs?

Figure 4 shows the CO(2–1) maps binned in 21 km s^{-1} channels to emphasize the main clumps. We used the program GAUSSCLUMPS (Stutzki & Güsten 1990; Kramer et al. 1998) to fit Gaussians to the substructures inside the CO filaments. Table 1 summarizes the results of the fits. The clumps have apparent sizes (convolved with the $2.5''$ beam) of $2.5''$ to $4.6''$. While some of the clumps are slightly resolved along their major axis, all of them are unresolved along their minor axis, and our upper limit on their deconvolved width is about half the beamwidth, or $1.3''$ (450 pc). To estimate the mass, we derived the CO line luminosity, L'_{CO} , with the formula of Solomon et al. (1997), and then applied a standard conversion factor of $4.6 M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$. With this factor, the estimated gas mass of each clump is $\sim 5 \times 10^7 M_\odot$, and the total gas mass ($\text{H}_2 + \text{He}$) in the CO east filament region is $4 \times 10^8 M_\odot$.

The observed brightness temperatures of the clumps are 0.39 to 0.63 K, which is one to two orders of magnitude too low for normal, optically thick molecular clouds. Evidence that this CO is indeed optically thick comes from the observations with the IRAM 30 m telescope by Salomé et al. (2008). A comparison of the 30 m CO(1–0) and (2–1) brightness temperatures convolved to the same beamsizes ($22''$) and centered on the eastern filament region gave a line ratio close to unity, consistent with optically thick line radiation. One possibility to reconcile the low observed brightness temperatures with their much higher expected values is that each clump is actually a complex of several Giant Molecular Clouds (GMCs). For typical Milky Way GMCs, the CO brightness temperatures are 20 to 40 K, the gas mass is $10^6 M_\odot$, and the typical radius is 30 pc ($0.1''$ at the distance of NGC 1275). If there were 10 such GMCs in each of the clumps on our maps, then the area filling factor within our $2.5''$ beam would be $f_a \sim 1$ to 2%. For GMCs with such a mass and radius, the volume densities are several hundred H_2 molecules cm^{-3} , and the surface densities are $\sim 10^{22} \text{ cm}^{-2}$. For comparison, the gas masses and extents of Milky Way-type GMCs are similar to the mass and size of the star cluster found in the Eastern filament by Shields & Filipenko (1990), so the CO clumps on our

Fig. 1. *Top:* integrated CO(2–1) intensity (contours) superposed on an H α image (Conselice et al. 2001) of NGC 1275. The inteferometer data were averaged over velocity offsets from -180 to -5 km s $^{-1}$. Contour steps are 1.6 Jy km s $^{-1}$ beam $^{-1}$. The white circle shows the inteferometer primary beam, and the grey ellipse at lower left, within the circle, shows the synthesized beam of $2.7'' \times 2.5''$ for the merged single-dish+inteferometer data. The CO spectra are from single pixels in regions A, B and C. The CO(2–1) spectrum of region D, the center of NGC 1275, is from the single-dish data only, and indicates an even larger amount of molecular gas in the galaxy’s center, with a much greater line width than in the filaments. Intensities of the spectra are in mJy in the $2.7''$ beam, except for region D, which is in units of mJy in the single-dish $11''$ beam (black circle around region D). Velocity offsets are relative to 226.559 GHz. *Bottom:* integrated CO(2–1) intensity superposed on the hot gas mass distribution derived from 0.5 keV X-ray observations of NGC 1275, from Fabian et al. (2006). CO contours, primary beam and synthesized beam are as marked in the upper diagram.

Fig. 2. Upper: mean CO(2–1) intensity along the filament, with contour steps of $0.5 \text{ Jy km s}^{-1} \text{ beam}^{-1}$. Lower: isovelocity contours, in steps of 10 km s^{-1} . The lines labeled 1 to 4 mark the position-velocity slices in Fig. 3. The beam (lower left) is $2.2'' \times 2.0''$.

maps could conceivably be the birth sites of star clusters. It remains to be explained why only one young optical star cluster, with HII region, is seen among all of these presumed GMC associations, and so why the rate of star formation is unusually low. The molecular gas may not be in GMCs at all. It would then not be dense enough to form stars. Higher spatial resolution observations are planned to look for smaller structures inside the eastern filament. The presence of magnetic field inside the filament might also help to prevent the molecular gas to be gravitationally unstable and thereby decrease the star formation efficiency. Magnetic pressure would also help to confine the gas inside those puzzling extremely long and thin filaments.

4. Comparison with bubble models

These CO observations show a complicated velocity pattern in the filament that extends from region A through region C (Fig. 1, upper). From region A to the zero position, the transverse gradient in the line-of-sight velocity is positive, with a value of $+40 \text{ km s}^{-1}/2.1 \text{ kpc}$. Over region C, the velocity gradient is negative with a value of $-120 \text{ km s}^{-1}/2.1 \text{ kpc}$. If these sections are continuous structures, the apparent transverse gradients are $+0.02 \text{ km s}^{-1}/\text{pc}$ and $-0.06 \text{ km s}^{-1}/\text{pc}$, comparable to velocity gradients through molecular clouds or along spiral arms in our Galaxy. Similar large-scale motions of $\sim 100 \text{ km s}^{-1}$ over distances $\sim 20 \text{ kpc}$ have been observed in H_2 and Pa lines by Jaffe et al. (2005) from BCGs in other clusters of galaxies. If the eastern filament is on the front side of NGC 1275, then the velocity shifts, which are blue-shifted relative to the systemic velocity, indicate outflowing material, as deduced for the $\text{H}\alpha$ filaments by

Fig. 3. $P - V$ plots of CO(2–1) parallel to the CO filament's major axis (PA $+70^\circ$; upper panels) and minor axis (PA -20° ; lower panels). Panel numbers 1 to 4 correspond to the lines in Fig. 1. Labels A, B, C indicate the CO peaks (Figs. 1 and 3). Contours are by 8 mJy/beam .

Hatch et al. (2006). If the eastern filament is on the rear side of the galaxy, then the blue-shifted CO indicates infalling material along the filament.

In the latter case, the inflow may be explained by the model proposed by Revaz et al. (2008), in which the “heavy” giant molecular clouds (GMCs) fall back in a thin stream on the central axis of the buoyantly-rising bubble. According to this model high temperature filaments of ionized gas resulting from up-lifted ambient hot gas could have cooled and formed the observed eastern filament. Once the plasma temperature drops below 10^6 K , the gas is no longer pressure-supported and falls back

Fig. 4. CO(2–1) maps, centered on the eastern filaments of NGC 1275, and binned in 21.2 km s^{-1} channels to show the main clumps, numbered as in Table 1. Contour steps are $8.9 \text{ mJy beam}^{-1}$ (4σ). The beam is $2.2'' \times 2.0''$. Position offsets are relative to the map center at $03^{\text{h}}19^{\text{m}}50.0^{\text{s}}$, $+41^{\circ}30'47.0''$ (J2000), marked with a cross. Velocity offsets (*upper left corners*) are relative to 226.559 GHz .

Table 1. CO clumps in the eastern filament region.

Clump number	Position offsets		Velocity offset	Peak line flux	Smoothed size		linewidth	CO luminosity	Gas Mass
	RA (arcsec)	Dec. (arcsec)	(km s^{-1})	(Jy beam^{-1})	ΔRA (arcsec)	ΔDec (arcsec)	$FWHM$ (km s^{-1})	($10^7 \text{ K km s}^{-1} \text{ pc}^2$)	($10^7 M_{\odot}$)
1	+5.2	+1.5	−63.6	0.16	2.5	3.3	29	2.1	9.6
2	+1.2	+6.3	−84.9	0.13	4.6	2.5	15	1.2	5.6
3	−1.9	+4.4	−79.3	0.12	2.5	2.5	17	0.7	3.3
4	−0.5	−0.4	−37.1	0.11	2.5	4.0	25	1.5	6.9
5	−2.0	+0.0	−89.9	0.11	2.5	3.1	31	1.4	6.5
6	+5.8	+2.1	−84.7	0.10	2.5	2.6	23	0.8	3.6
7	−5.3	−1.7	−148.2	0.10	2.7	3.7	31	1.6	7.6

Estimated errors are $\pm 20\%$ in all quantities. Clump sizes ($FWHM$) are convolved with the $2.5''$ beam. Gas masses ($\text{H}_2 + \text{He}$) are for solar abundances (as for iron-line X-rays) and $M/L'_{\text{CO}} = 4.6 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$. Clumps 1 and 6 are within region A but have different velocities, and clumps 4 and 5 are within region C (Fig. 1).

towards the center. This scenario naturally reproduces part of the observed velocity gradient, because cold gas emerges from higher-temperature gas at the top of the filament with nearly zero velocity offset relative to the systemic velocity of NGC 1275, while cold gas at the bottom of the filament has sped up by falling in. Figure 1 (position-position diagram) as well as Fig. 2

(position-velocity) may be qualitatively reproduced (see Fig. 5) by the model 2 of Revaz et al. (2008) at $t = 250 \text{ Myr}$. Figure 5 assumes that the cold filament is behind the galaxy (to produce a net blue shift), and being viewed down its length, i.e., observed at an angle of 10° from our line of sight. In this model, the cold gas is produced between 25 and 50 kpc, corresponding to a

Fig. 5. *Left:* surface density of cool gas in simulated filaments in model 2 of Revaz et al. (2008), at $t = 250$ Myr. The model filament is inclined at 10° to the observer's line of sight. *Right:* position-velocity diagram for the same filament. The red box shows a $p-v$ sector in the model that is comparable to that of the eastern filament region observed in CO.

projected observed distance of 5 kpc to 10 kpc. A velocity gradient larger than 100 km s^{-1} is easily reproduced. The mass enclosed in the red box is equal $3 \times 10^8 M_\odot$, similar to the $4 \times 10^8 M_\odot$ observed in CO. If the viewing angle along the line of sight is larger than 45° , the velocity gradient is reduced and the data are harder to reproduce. In this scenario, the velocity gradient also tells us that the cold gas, if free falling, may not have been created too far away from the center, otherwise, the maximal velocity (at the bottom of the filament) should be much higher than observed. It is possible, though, that GMC are globally subject to ram pressure on the hot gas, and are somewhat braked in their free-fall, dragging the dense clumps gravitationally locked in. Magnetic fields might also play an important role in holding clouds together.

5. Origin of the molecular gas

The cold molecular filament mapped here is part of an extended (~ 30 kpc) network of filamentary structures seen in $\text{H}\alpha$ and soft X-ray emission. No such filamentary structure is ever seen in galaxy interactions, but is specific to *cooling flow galaxies*. There is a good correspondence between ionized gas and molecular gas in the filaments, and also a very good correspondence between the morphologies of the CO emission and the gas that radiates at higher temperature in X-rays (Fig. 3). The single-dish map from the IRAM 30 m telescope (Salomé et al. 2006, their Fig. 5) showed no sign of rotation of the molecular gas around the center of NGC 1275, on scales of $\sim 60''$ (20 kpc). The CO lines have negative velocities on both sides of the galaxy's center. This surprising pattern has also been confirmed by CO(2–1) mapping with the SMA (Lim et al. 2008). This molecular gas was interpreted as being either flowing toward the central object or outflowing in a wake of an expanding bubble. The lack of a rotation pattern on these scales makes it unlikely to be gas tidally stripped from another galaxy. It also rules out a large amount of rotationally-supported cold gas in the galaxy potential well. In our interpretation the gas dragged outwards by the rising bubble is first hot, and cools progressively. We think that the molecular gas detected in CO is associated with the cooled gas that may be partly falling back on the galaxy center.

The lack of any rotation pattern closer to the center is puzzling and also supports a scheme where the filament network is spread all around NGC 1275. If we assume that the cold gas is in free fall in the galaxy potential well, then a model of cold

gas flowing down towards the galaxy from all directions could explain the absence of global angular momentum and prevent any rotation closer to the center. The filaments are not all radial, but are perturbed and asymmetric, with a non-zero impact parameter. In isolation, any one filament would then give rise to a certain rotation. But the infall of several filaments in any direction cancels out the net angular momentum. The large velocity dispersion in the central region (Region D in Fig. 1) supports this scenario. When compared to the very narrow spectra of region A, B and C, a natural explanation is that the center could be made of a collection of such filaments, streaming in random directions. The motions in the large-linewidth central region, however, could also partly be due to the energetics of the AGN that powers the central region.

There is no evidence of dust in the filaments. No extinction is seen associated with the $\text{H}\alpha$ filaments, while dust associated with the foreground high velocity system (at $+3000 \text{ km s}^{-1}$) is conspicuous (Keel 1983). The lack of significant amounts of dust in the filament, presumably due to high sputtering rates, implies that the CO forms mainly in the gaseous phase. Star formation activity is low. It is only seen inside the filament in the Shields and Filipenko cluster. So the cold gas reservoir observed here is not forming stars very efficiently.

6. Conclusions

Our interferometer observations of the eastern filament region reported in this paper show that we can now spatially resolve dense cold gas along thin and elongated filaments coinciding with the well-known $\text{H}\alpha$ emission around NGC 1275. This cold gas is also resolved into narrow linewidth-emitting clouds (30 km s^{-1}), in contrast to the broad lines (200 to 400 km s^{-1}) detected in the majority of our single dish detections (Edge et al. 2001; Salomé & Combes 2003). The interferometer retrieves all of the CO emission found in single-dish observations, which implies that we have not missed any more large-scale CO emission. The east filament is resolved into molecular gas concentrations that could be cooling separately. The molecular gas has probably formed in the spots where it is observed. If the filament is on the rear side of the galaxy, then its morphology, total mass, and kinematics is consistent with the scenario proposed by Revaz et al. (2008) where the AGN feedback drags warm gas to greater radii, where it undergoes runaway cooling. This process can create the east filament observed in CO, possibly composed of GMCs partly falling toward the center of NGC 1275.

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