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Letter to the Editor

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CO emission along the anomalous arms of NGC 4258

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Summary. We present CO observations of NGC 4258 made with the IRAM 30-meter telescope. CO emission has been detected toward NGC 4258 in the central region and *along* the anomalous arms up to distances of about 2 kpc from the center. Cuts perpendicular to the anomalous arms show that the CO is concentrated along the Hα emission. At distances greater than 2 kpc, no CO has been detected neither along the extensions of the optical structures nor further out along the radio ridges. The molecular mass associated with each anomalous arm is estimated to be about $3\,10^8\,M_\odot$. The strong concentration of the molecular gas in the inner parts of the Hα arms and the high associated H_2 mass are facts which are not expected by any existing model.

Key words: interstellar medium, molecules – galaxies, individual: NGC 4258

1. Introduction

The spiral galaxy NGC 4258 is known for its anomalous Hα and nonthermal radio arms perpendicular to the normal spiral arms (van der Kruit et al., 1972). Several models have been proposed to explain this phenomenon. Its origin must probably be sought in the nucleus of NGC 4258 which, however, does not show any strong activity at present. Most of the characteristics of the anomalous arms, such as the symmetry with respect to the center, or the properties of the emission lines (pure Hα line emission with no continuum, line ratio between Hα and [NII]) are reminiscent of the optical and radio jets currently observed in active galaxies (see e.g. Miley, 1983). Moreover these anomalous arms are invisible in the blue and red optical continua and do not show any signs of star formation (van der Kruit et al., 1972 and Martin et al., 1989). This is corroborated by the lack of ultraviolet continuum around 2000Å (Courtes, private communication). Finally, it appears likely that, in NGC 4258, the anomalous arms lie within the disk of the galaxy (see van Albada and van der Hulst, 1982; Krause et al., 1984; Hummel et al., 1989).

Recent observations of linear radio polarization (Hummel et al., 1989) put severe constraints on the existing models: the changes of the spectral index along and across the radio ridges could qualitatively, be explained by a model in which an expulsion of material occured in or under a small angle with the plane of the galaxy such as the expulsion model of van der Kruit et al. (1972). According to this model, the radio and Hα emissions along the anomalous arms are due to interaction between gas expelled from the nucleus with the interstellar gas in the disk of the galaxy.

CO emission in the J=1-0 transition has been recently observed in NGC 4258 with the Nobeyama 45-m telescope (Sofue et al., 1989), the 12-meter Kitt Peak telescope (Adler and Liszt, 1989) and the Caltech interferometer (Martin et al., 1989). Sofue et al. (1989) detected a massive cloud in the nucleus and weaker emission within the central 40″x 60″but no obvious association of the CO emission was found with the anomalous arms (note, however, that the r.m.s. noise and the pointing errors of these observations may have been underestimated). Martin et al. (1989) resolved the central cloud in two components lying on each side of the nucleus suggesting a channel corresponding to the Hα feature.

This paper presents new CO observations in the $J = 1-0$ transition obtained with the IRAM 30-meter telescope along the anomalous arms of NGC 4258 out to distances of 4 kpc from the center.

2. Observations and results

The observations were made in September 1989 with the IRAM 30-meter telescope on Pico Veleta near Granada, Spain. The telescope beam size at the ^{12}CO$(1-0)$ frequency is 21″. Pointing was checked by broadband continuum observations of planets: the derived errors were about 4 to 5 arcsec during our run. We used a SIS receiver in single sideband mode with $T_{rec} \sim 290$ K and $T_{sys} \sim 1200$ K outside the atmosphere. The antenna temperature scale used throughout this paper is given in terms of main beam brightness temperature, T_{mb}. A filterbank of 512 x 1 MHz channels provided a velocity resolution of 2.6 km s^{-1} per channel. The spectra were smoothed to a resolution of 10.4 km s^{-1}. They were taken with the secondary reflector switching 4 arcmin in azimuth. The total integration time was 16 min for most of the points. Linear baselines were fit to the data.

Figure 1 shows the positions of our ^{12}CO$(1-0)$ emission measurements on the Hα images of NGC 4258 from Martin et al. (1989). Spectra were taken at 12″intervals along and perpendicular to the anomalous arms and at smaller intervals in their southern part and in the nuclear region. A few measurements were also made at the far ends of the Hα features along the radio ridges.

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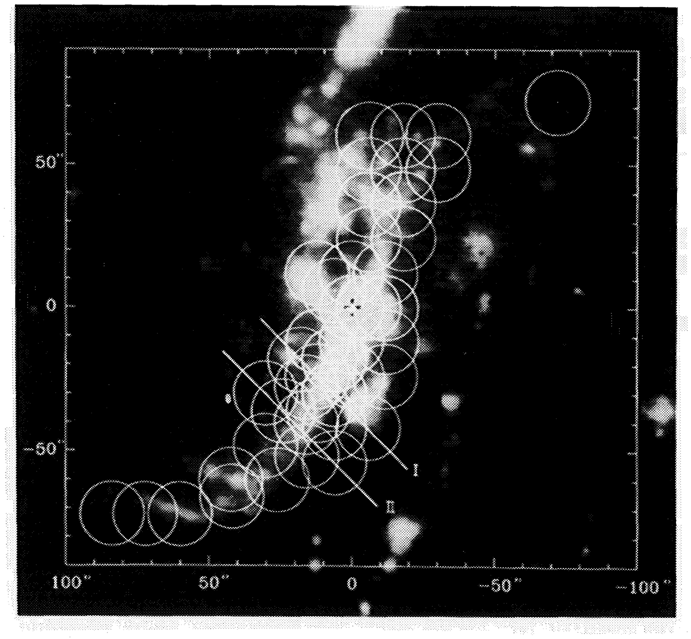

Fig. 1. Monochromatic Hα CCD image of NGC 4258 from Martin et al. (1989). The Hα-arm is clearly visible with its S-shape form. Circles representing the IRAM 30-meter beam size of 21″at ^{12}CO(1 − 0) show all observed positions. The nuclear position at (0, 0) = ($12^h16^m29\overset{s}{.}42; 47°34'53\overset{''}{.}2$) (1950.0) was taken from van der Kruit et al. (1972)

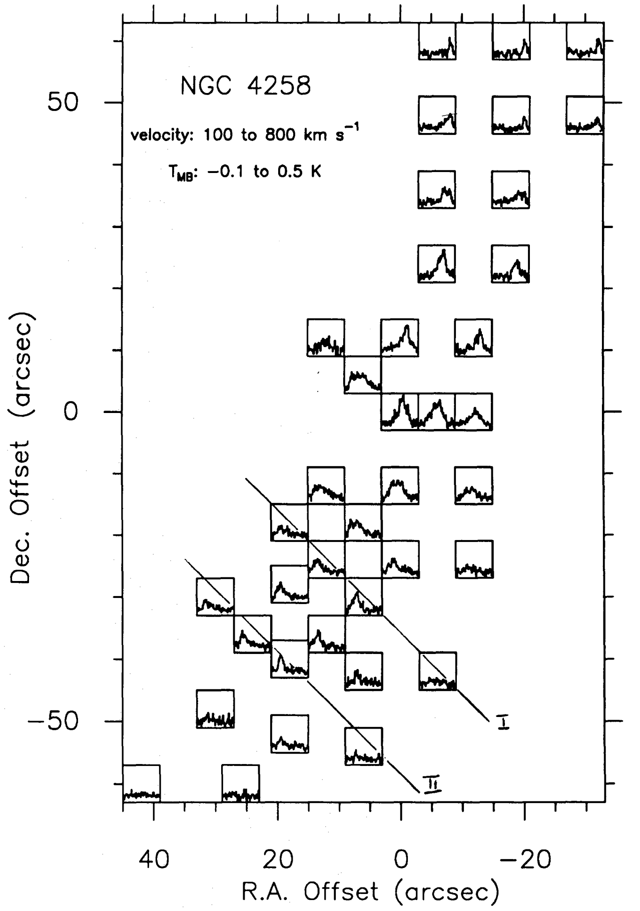

Fig. 2. ^{12}CO(1 − 0) spectra of NGC 4258 at the positions shown in Fig. 1 up to distances of about 2 kpc along the anomalous arms. The spectra have been smoothed to a velocity resolution of 10.4 km s^{-1}.

Figure 2 presents the ^{12}CO(1 − 0) spectra of the observed positions along the anomalous arms out to distances of about 1 arcmin from the nucleus (corresponding to about 2 kpc for a distance of 6.6 Mpc and an inclination angle of 72°). The noise in the majority of the spectra shown in Fig. 2 is 30 to 40 mK r.m.s. The ^{12}CO(1 − 0) emission reaches a maximum in the center of NGC 4258 with $T_{\rm mb} \sim 350$ mK and a line width of about 200 km s^{-1} around the systemic velocity of 457 km s^{-1} . Further out, the CO emission follows the anomalous arms up to distances of about 2 kpc. The mean velocities and the widths of the CO lines along the Hα anomalous arms of NGC 4258 are illustrated in Fig. 3. While the line intensity varies only slightly between 200 and 350 mK, systematic changes in line width and velocity are observed. The velocity varies gradually from 220 to 700 km s^{-1} from south to north, in the sense of normal galactic rotation. The line width of the CO emission decreases systematically from the center to the south and the north reaching a minimum of 51 ± 6 km s^{-1} in the north at the position (-18″, 48″) and 95 ± 6 km s^{-1} in the south at (18″, -42″). Both positions coincide with the points of the anomalous arms where the Hα emission starts to be fainter and then splits, further out, into two branches (see Fig.1). In the southern Hα arm, position (18″, -42″) corresponds to a local maximum with $T_{\rm mb} = 260$ mK. No CO emission was detected further out along the south-eastern and north-western radio ridges: averaging all the spectra taken in the south-east at Dec. offset smaller than -60″yields a noise of 25 mK r.m.s. Assuming that for the south-eastern averaged spectrum a line with a width of 50 km s^{-1} and an intensity of 2 σ could have been detectable, this negative result means a decrease in mass surface density of about a factor of ten when compared to the CO emission along the inner 2 kpc of the southern Hα arm. A similar situation arises in the northern radio ridge at the position (-72″, 72″) where no emission was found down to a noise of 35 mK r.m.s.

The southern part of the anomalous arms is well separated from the normal spiral arm and, hence, better suited for a detailed analysis of the relation between the CO and the Hα emissions in the anomalous arm of NGC 4258. The two cuts through the southern Hα arm (marked I and II in Figs. 1 and 2) show that the CO emission peaks at the Hα arms. An equivalent check is less straightforward in the northern part due to the proximity of the anomalous arm to the northern *normal* spiral arm. A more complete mapping of the northern area is needed in order to disentangle the contributions of both the anomalous arm and the spiral arm.

The CO luminosity, $L_{\rm CO}$, derived from our ^{12}CO(1 − 0) measurements averaged along the anomalous arms of NGC 4258 is 1.5×10^8 K km s^{-1} pc^{-2}; for the central region (within two beam areas), we derive 2×10^8 K km s^{-1} pc^2. Assuming a standard $N(H_2)/I_{\rm CO}$ conversion factor (Young and Scoville, 1982) of $4 \times 10^{20} \cos i\, H_2\, {\rm cm}^{-2} ({\rm K\, km\, s}^{-1})^{-1}$ or the equivalent ratio $M_{H_2}(M_\odot) = 6 L_{\rm CO}({\rm K\, km\, s}^{-1}\, {\rm pc}^2)$, we derive a mass of molecular hydrogen of $M_{H_2} \simeq 3\, 10^8 M_\odot$ associated with each anomalous arm. For the central region, we derive $M_{H_2} \simeq 4\, 10^8 M_\odot$ yielding a total mass of molecular hydrogen of $M_{H_2} \simeq 10^9 M_\odot$. This mass derived from a conventional

CO/H_2 conversion may be an unreliable estimate of the total mass of molecular hydrogen: photodissociation of CO, likely to occur in the extreme physical conditions pertaining along the anomalous arms, will lead to an underestimate, whereas enhanced gas heating and/or metallicity effects will lead to an overestimate of the molecular mass.

3. Discussion

The present $^{12}CO(1-0)$ observations of NGC 4258 show that about $10^9 M_\odot$ of molecular gas is distributed in the center and along the anomalous arms out to distances of about 2 kpc. As emphasized in the southern part of the anomalous arms, the CO remains concentrated *along* the Hα emission. At distances greater than 2 kpc, no CO is detected neither along the extensions of the optical structures nor further out along the radio ridges.

The model by van der Kruit et al. (1972) reproduces some of the salient facts of the anomalous arms (see discussion by Hummel et al. (1989) and Martin et al. (1989)). This model assumes that after expulsion from the nucleus, the gas clouds were "braked by the gas already present *in* the disk and carried along with the rotation" (van der Kruit, 1974). The expelled clouds are now distributed along the Hα arms *and* the radio ridges. The present observations further support the model in its basic assumption namely that the Hα arms extend in the plane of the galaxy. The spatial agreement in the inner 2 kpc of the anomalous arms between the distributions of the radio, optical and $^{12}CO(1-0)$ emissions suggests indeed a physical connection of the plasma, the shocked gas and the neutral gas, respectively. Assuming that the CO layer has a typical scale height of 50 to 100 pc constrains the angle at which the gas was ejected from the nucleus into the plane of the galaxy to values between $1\overset{\circ}{.}5$ and 3°. A similar small angle is required to explain the symmetry of depolarization and rotation measure of the radio polarization between 8 and 15 kpc in both anomalous arms (Hummel et al., 1989). Finally, the amount of mass associated with each arm ($\sim 3\,10^8\,M_\odot$) excludes, on both energetical and dynamical arguments, that the anomalous arms extend *outside* the plane of the galaxy. Theories proposing that the anomalous arms lie outside the plane, such as those of Sofue (1980) and Sanders (1982), are thus unlikely.

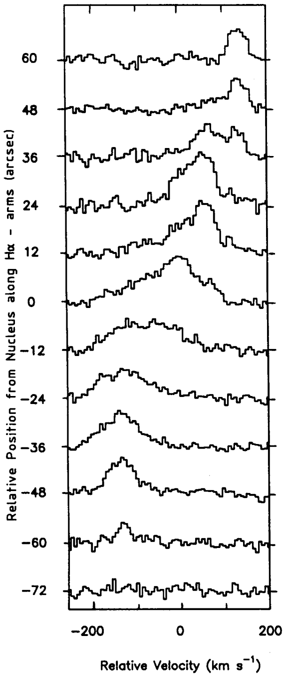

Fig. 3. Averaged $^{12}CO(1-0)$ spectra along the Hα-arm of NGC 4258. Velocities are given with respect to the systemic velocity of 457 km s^{-1}

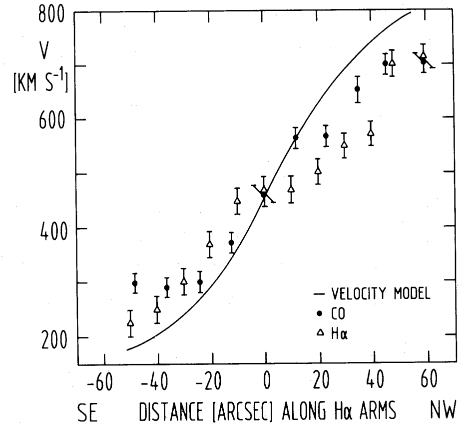

Fig. 4. Comparison of the velocities along the Hα-arm of NGC 4258 as derived from our $^{12}CO(1-0)$ measurements (filled dots, averaged spectra as shown in Fig. 3) with the Hα velocities taken from the observations of van der Kruit (1974) (triangles) and velocities (perpendicular to the line of sight) corresponding to a rotation model as given by an der Kruit (1974) – solid line

The present observations enable to study the velocity field along the inner 2 kpc of the anomalous arms. Figure 4 compares the CO velocities along the anomalous arms as derived from the average spectra shown in Fig. 3 at the peak intensities with the Hα velocities as measured by van der Kruit (1974). A basic rotation model, as approximated by van der Kruit (1974) from Hα observations of the normal spiral arms, is shown as a full line. Whereas the CO and Hα velocities agree with each other (taking into account that the optical velocities are reliable within 50 km s^{-1}), systematical deviations from the circular rotation are present both in the ionized gas and the molecular gas. As already pointed out by van der Kruit, the rotation velocities found in the anomalous arms are *lower* than the basic rotation, the differences amounting to 50–100 km s^{-1}. This can be interpreted as a slower rotation or a superposition of rotation and radial velocity directed outwards. Note, however, that the rotation curve in the inner parts of NGC 4258 is only poorly known.

The location of the anomalous arms *inside* the plane of the galaxy and the velocity field along them seem thus to be consistent with the predictions of the expulsion model by van der Kruit et al. (1972). However, the distribution of CO in the inner parts of the anomalous arms and the abrupt decrease of surface mass density of a factor of ten at about 2 kpc are facts which are not predicted by this model. The derived mass ($\sim 6\,10^8\,M_\odot$) in the inner 2 kpc exceeds by about an order of magnitude the estimate by van der Kruit et al. (1972) of the total expelled mass i.e. 10^7 to $10^8\,M_\odot$ which was predicted to reside mainly along the radio ridges where we did not detect CO emission. The kinetic energy involved increases by a similar factor amounting to 10^{58} erg for an average expulsion velocity of 1000 km s^{-1}. This leaves open the question of the nature of the expelled gas.

The lack of atomic hydrogen along the anomalous arms (van Albada, 1978) indicates that, in the inner 2 kpc, most of the hydrogen is in molecular form; moreover, a small fraction, corresponding to a few $10^6\,M_\odot$, is ionized and seen through the Hα line emission (Martin et al., 1989). This ionized gas may correspond to the lower density atomic envelopes of the molecular clouds which have been shock-ionized by the gas expelled from the nucleus. The ionization of the outer layers of the molecular clouds may also account for the fact that, despite the large amounts of molecular gas, the Hα emission remains so strong and uniform along the anomalous arms. This effect can be enhanced if the molecular gas has an inhomogeneous distribution. In the outer parts of the anomalous arms, since HI and CO are lacking, all the available gas (which may have been the previously low-density HI gas of the galactic disk) has been probably shock-ionized and is presently seen in the Hα line emission and the non-thermal radio radiation.

The continuity in the Hα brightness is only seen along the portion of the arm containing CO. Further out, as is clearly illustrated in the southern arm, after the CO distribution ends, the optical line emission starts to be diffuse and then splits into two branches. These facts leave the impression that the molecular gas plays a role in the collimation of the structure.

As compared with the present knowledge on the morphology and dynamics of the anomalous arms, our information on the physical properties (temperature, density) is very uncertain. Systematic optical spectroscopy along the anomalous arms should be done in order to derive the temperature of the ionized gas and the still unknown ionization mechanism. First estimates for the density of the molecular gas can be derived from the present observations: assuming a typical width of 250 pc (i.e 7 arcsec) for the CO distribution along the anomalous arm yields a typical column density of molecular hydrogen of $\sim 10^{22}\,H_2\,cm^{-2}$; with a scale height of 50 pc, the molecular hydrogen density amounts to $\sim 60\,cm^{-3}$. This is, however, a lower limit if the CO distribution is inhomogeneous. Probing the higher rotational transitions of CO would further constrain the characteristics of the neutral gas (density and temperature). These numbers are a prerequisite for any further analysis of the anomalous arms of NGC 4258.

Despite a precise knowledge of the physical conditions of the anomalous arms, characteristics such as their symmetry with respect to the nucleus in the Hα emission, the CO distribution and the radio polarization, and, the non-thermal nature of their radio emission strongly suggest properties of radio and optical jets observed in radio galaxies. The nucleus of NGC 4258 does not presently show the signs of powerful activity usually associated with such energetical phenomema. The relatively weak infrared luminosity of the nucleus, $6\,10^8\,L_\odot$, as extrapolated from 10 μm observations (Rieke and Lebofsky, 1978) and the total infrared luminosity of NGC 4258 ($1.23\,10^{10}\,L_\odot$, Rice et al., 1988) exclude starburst-like mechanisms. The radio and Hα luminosities of the nucleus are low pointing also to a "quiet" nucleus. According to Ford et al. (1984), NGC 4258 was not detected with the Einstein X-ray observatory. Water maser emission has been monitored over the past years in the nucleus of NGC 4258: with an associated luminosity of $150\,L_\odot$, it exhibits rapid variability (85 days period) yielding an extent of the emitting region smaller than 10^{16} cm (Claussen et al., 1988). The original classification by Seyfert has been confirmed by optical spectroscopy of the nucleus which shows broad ($\sim$ 1700 km s^{-1}) weak Hα and strong [OI] lines (Stauffer, 1982; Fillipenko and Sargent, 1985): line ratios indicate that the nucleus of NGC 4258 is intermediate in type between models of shock ionization and power-law photoionization. Finally, it is of interest to note that NGC 4258 has a companion located $\sim$ 12 arcmin NW from the nucleus, NGC 4248 (van Albada, 1977), visible on the POSS blue plate and on the 60 μm IRAS isophots (Rice et al., 1989): the redshift measurement locates this companion at a distance of 37 kpc from NGC 4258 (Dahari, 1985). Further studies should enable to check if any physical connection is present between both galaxies.

As shown by Wilson (1982), faint twisted jets up to a few kpc in length are found inside the nuclei of Seyfert galaxies. NGC 4258 may be an example of a jet associated with a Seyfert galaxy. Relatively nearby, NGC 4258 remains a unique opportunity to investigate the interaction of a jet-like phenomenon with both the atomic and neutral gas of the galactic disk.

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