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LETTER

Letter to the Editor

CO(4–3) and CO(3–2) studies of M 51 and NGC 6946

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Abstract. We have mapped several nearby galaxies in the CO(4–3) line transition with the Heinrich-Hertz-Telescope on Mt. Graham, Arizona, during an excellent weather period in December 1998. Here we report on our observations of M 51 and NGC 6946. The results suggest a concentration of highly excited CO gas to the nuclei of these galaxies. Moreover, in both objects CO(4–3) line emission was also detected for the first time in the spiral arms, several kiloparsecs away from the centre.

Key words: galaxies: individual: M 51 – galaxies: individual: NGC 6946 – galaxies: ISM – galaxies: spiral – radio lines: galaxies

1. Introduction

The study of galaxies in the higher CO line transitions, as well as in the various isotopic species, should allow us to determine the physical conditions in the emitting regions. In the case of thermalized excitation temperatures of 55 K or 33 K are required to excite the $J = 4$ or $J = 3$ level, respectively. Alternatively the Large Velocity Gradient (LVG) analysis (see e. g. de Jong et al. 1975) should allow us to determine the temperature, the density and the optical depth from the observed line ratios. Following the systematic observations of many galaxies in the CO(1–0) and CO(2–1) lines, the attention has now moved to the higher line transitions. Recently 345 GHz observations of several galaxies (Mauersberger et al. 1999; Wielebinski et al. 1999) were reported, showing that this higher line transition (which in general is due to warm and dense gas) is easily detectable in many galaxies and that it can be found even far off from the centre.

There are up to now only a few published papers on CO(4–3) line observations in external galaxies. In fact only four of the most intense galaxies were observed so far. The pioneering work of Güsten et al. (1993) showed data on three points in M 82, one in IC 342 and two in NGC 253. A paper by White et al. (1994) gave CO(4–3) and C I maps of a region $40'' \times 30''$ in extent in the centre of M 82. More extensive studies of NGC 253 in the C I and CO(3–2) line with some CO(4–3) points were reported by Israel et al. (1995). Recently Petitpas and Wilson (1998) have published a larger CO(3–2) map of M 83 and a CO(4–3) map covering $20'' \times 20''$ of the central region of this galaxy. We note that all these four objects are considered to be active starburst galaxies.

The reason for this sparse data base is that only a few radio telescopes exist which are capable to make these sub-mm observations. We have used the 10-m Heinrich-Hertz-Telescope on Mt. Graham, Arizona, which has been designed for sub-mm observations. We have made extensive maps of several nearby galaxies in the CO(3–2) line, which we report elsewhere. In a short period of excellent weather in December 1998 we were able to make maps in the CO(4–3) transition of the central regions of six weaker, nearby galaxies. Here we report results on two of them, M 51 and NGC 6946.

2. Observations and data reduction

The observations were made on December 7th and 8th 1998 during a period of excellent weather at the 10-m Heinrich-Hertz-Telescope[1] (see Baars & Martin 1996) on Mt. Graham, Arizona, with the SORAL 490 GHz single-channel receiver. As the backend we used an 2048-channel Acousto-Optical Spectrometer supplied by the MPIfR. The usable bandwidth of the AOS was about 850 MHz, corresponding to $\sim 550\,\mathrm{km/s}$, with a spectral resolution of $0.312\,\mathrm{km/s}$. The weather during the observations was excellent with a zenith opacity of $\tau_{461\mathrm{GHz}} \sim 0.4$ most of the time; for a few scans of M 51 it was as high as 0.9 at the end of the observing run.

The receiver temperatures were between 170 K and 195 K (DSB), providing system noise temperatures of typically $T_{\mathrm{sys}} \sim 900 - 1400$ K, but T_{sys} went up to 4000 K in detoriating weather or for extremely low elevations. Simultaneous measurements of the opacity at 461 GHz by skydips and with the on-site installed 225 GHz taumeter yielded a ratio of $\tau_{461\mathrm{GHz}}/\tau_{225\mathrm{GHz}} \sim 10$. The beamwidth was measured during several pointing scans and varied between $17''$ and $18''$.

The observations were performed using the wobbling secondary reflector with a beam throw of $\pm 120''$ and a wobbler frequency of 2 Hz. Pointing observations on planets or point-

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[1] The HHT is operated by the Submillimeter Telescope Observatory on behalf of Steward Observatory and the MPI für Radioastronomie.

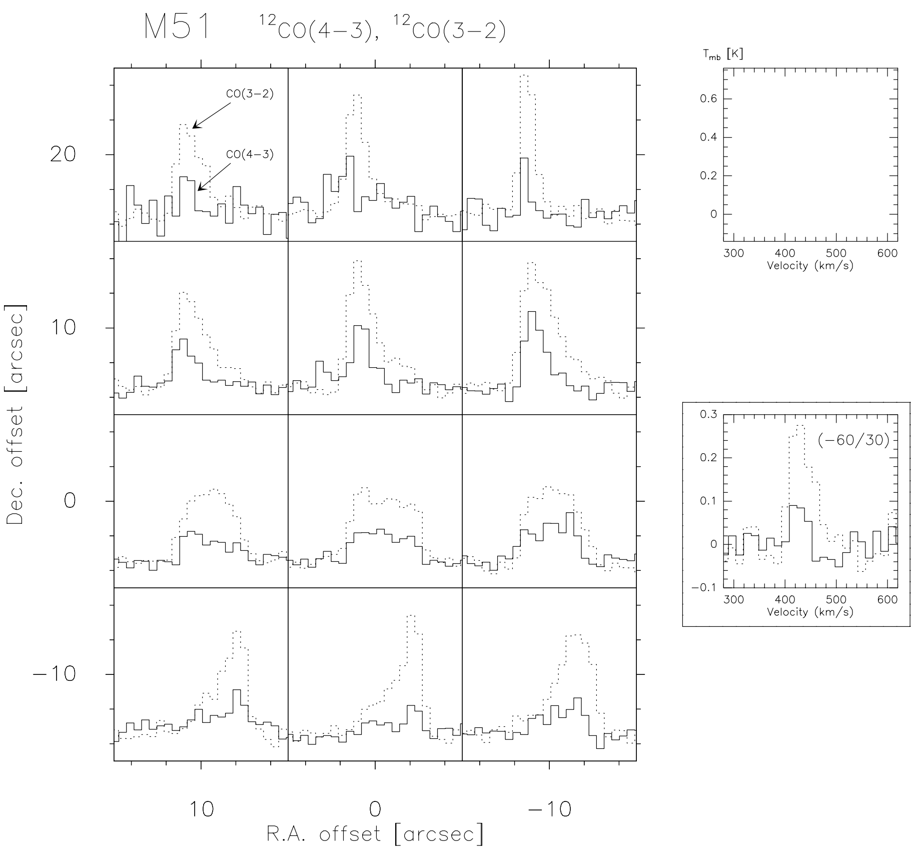

Fig. 1. The ^{12}CO(4–3) spectra at $17''$ resolution observed in M 51. Each profile is given as a function of the antenna pointing offset relative to the centre (R.A.(1950) $= 13^{\rm h}27^{\rm m}46\overset{\rm s}{.}1$, Dec.(1950) $= 47°27'14''$). In addition HHT observations of the CO(3–2) transition at $22''$ resolution are plotted as dashed lines. The scales of the velocity (in $\rm km/s$) and the temperature $T_{\rm mb}$ (in Kelvin) are indicated by the box in the upper right corner. In the box on the right the spectrum of a position on a dust lane of a spiral arm at an offset of $-60''/30''$ from the centre of the map is shown. Two $\rm H_\alpha$ regions are situated in the beam. All data have been smoothed to a resolution of $15\,\rm km/s$.

Table 1. Basic parameters of M 51 and NGC 6946

Source	R.A.(1950)	Dec.(1950)	D [Mpc]	Pos. Angle [°]	Incl. [°]	$v_{\rm lsr}$ [km/s]	Type
M 51	$13^{\rm h}27^{\rm m}46\overset{\rm s}{.}1$	$47°27'14''$	9.6 ($10''\hat{=}465$pc)	-10	20	470	SA(s)bc pec
NGC 6946	$20^{\rm h}33^{\rm m}48\overset{\rm s}{.}8$	$59°58'50''$	5.2 ($10''\hat{=}250$pc)	60	30	46	SAB(rs)cd

like line sources (like the stars χ Cyg and V Cyg) were carried out every 2 or 3 hours. The rms pointing uncertainty was found to be better than $2''$. The focussing of the telescope was checked twice a day (well after sunrise and sunset). Receiver temperatures were determined after each retuning using a cold load (at liquid nitrogen temperature) which was inserted into the beam, while system temperatures ($T_{\rm A}^*$ scale) were determined every 20 to 30 minutes, using a Hot-Sky-calibration procedure.

All results in this letter are given in main beam brightness temperatures ($T_{\rm mb}$), which are related to the antenna temperature, corrected for atmospheric absorption and spillover ($T_{\rm A}^*$) via $T_{\rm mb} = (F_{\rm eff}/B_{\rm eff})T_{\rm A}^*$. The main beam efficiency at our observing frequency was measured on Saturn to be $B_{\rm eff} \sim 0.38$, using a brightness temperature of 130 K (Hildebrand et al. 1985). The forward efficiency of the HHT at 461 GHz is about 0.76 (D. Muders, priv. comm.). The absolute calibration of our data were cross-checked by observations of χ Cyg which were compared to the flux given by Young (1995) and was found to be accurate to better than $10\,\%$. Furthermore, our results on NGC 6946 are in good agreement with the value published by Güsten et al. (1993). Taking all these factors into account, we estimate the absolute calibration accuracy to be better than 15%.

The data reduction was performed using the CLASS program available from the Grenoble software package. As the atmosphere was very stable we got very flat baselines, and only first order baselines have been subtracted from the spectra. Finally several single spectra on one position on the sky were added. We spent about five minutes for each position on source.

In this paper we present the maps of the two galaxies M 51 and NGC 6946. The maps show 12 and 19 positions in the central part of the galaxy. In M 51 we detected also emission in the spiral arm at a distance of $70''$ from the centre (Fig. 1). But the most striking result is the detection of CO(4–3) more than $180''$ away from the nucleus in NGC 6946 (Fig. 2).

3. Results

3.1. Results on M 51

The galaxy M 51 is a grand design spiral galaxy at a distance of $9.6\,\rm Mpc$. The CO(4–3) spectra shown in Fig. 1 have been smoothed to a velocity resolution of $15\,\rm km/s$. Even far from the centre of the galaxy (at $70''$ or $\cong 3\rm kpc$ galactocentric distance), on a dust lane of a spiral arm between two $\rm H_\alpha$ regions, CO(4–3) is detected. The spectra of the CO(3–2) transition obtained

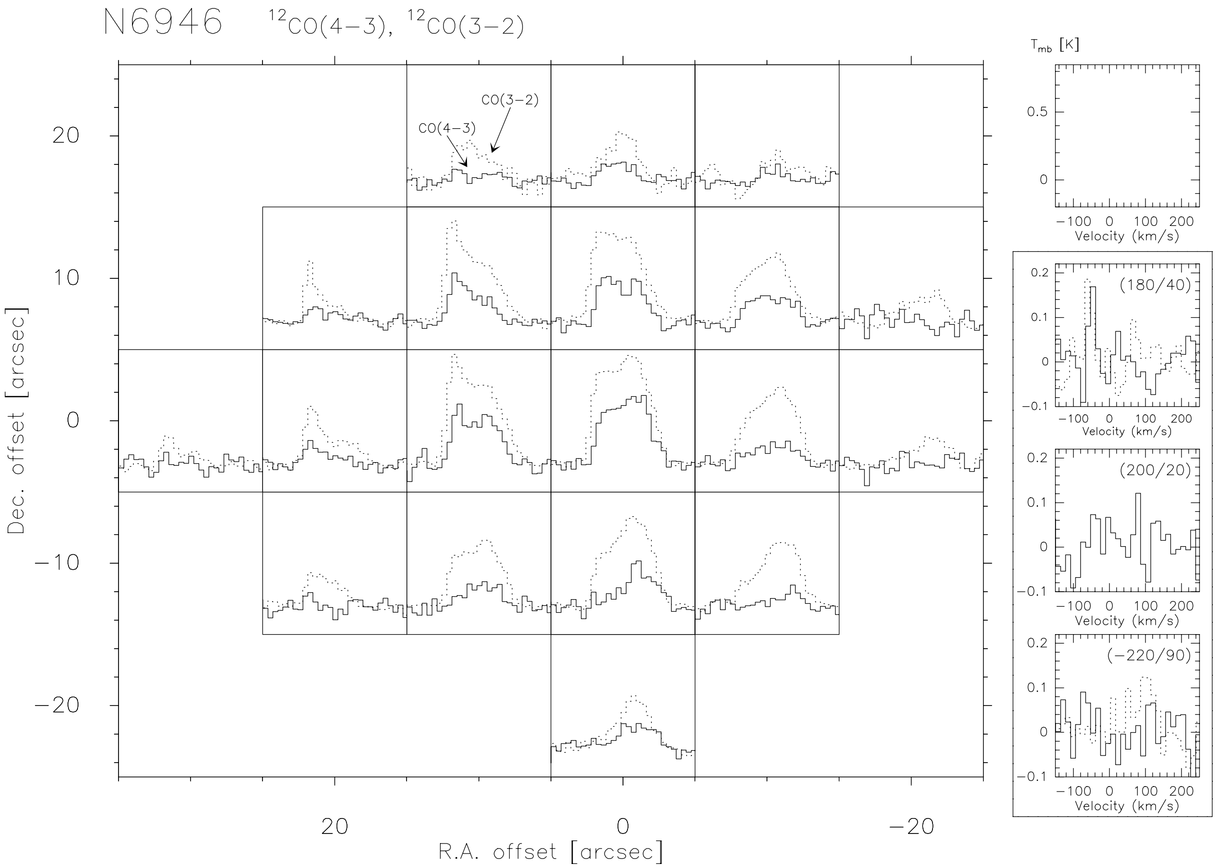

Fig. 2. The ^{12}CO(4–3) at $17''$ resolution spectra observed in NGC 6946. Each profile is given as a function of the antenna pointing offset relative to the centre (R.A.(1950) $= 20^{\rm h}33^{\rm m}48\overset{\rm s}{.}8$, Dec.(1950) $= 59°58'50''$). In addition HHT observations of the CO(3–2) transition at $22''$ resolution are plotted as dashed lines. The scales of the velocity (in $\rm km/s$) and the temperature $T_{\rm mb}$ (in Kelvin) are indicated by the box in the upper right corner. The spectra and relative coordinates of the three positions with strong HI emission near star-forming regions on the spiral arms are shown in the boxes on the right. All data have been smoothed to a resolution of $14\,\rm km/s$.

by Wielebinski et al. (1999) are also plotted in Fig. 1 as dotted lines. The shapes of the two transitions and their widths do not show significant variations, which confirms the high pointing accuracy.

We made a comparison of the integrated line emission in the two transitions CO(4–3) and CO(3–2) correcting for the different beams. For the central region we find a line ratio $[R_{4,3} = I_{\rm CO}$(4–3)/$I_{\rm CO}$(3–2)] of $R_{4,3} = 0.30 \pm 0.07$. Though there are not enough points for good statistics, a slight decrease in the line ratio can be seen from the very centre to larger radii where we find $R_{4,3} = 0.20 \pm 0.07$. This is the first indication that the density and excitation temperature of the molecular gas fall off from the centre of M 51. In the outer spiral arm the line ratio $R_{4,3}$ is $\cong 0.25$ which is an upper limit due to the different beams.

The critical conditions to excite the $J = 4$ level are concentrated to special regions of the galaxy, in contrast to $J = 3$ which can be found almost everywhere where CO(1–0) and CO(2–1) are detected (see Wielebinski et al. 1999). Using the CO(1–0) map of Nakai et al. (1994) we see a constant line ratio of $R_{3,1} = 0.50 \pm 0.1$ for the whole region covered by the CO(4–3) map, which also indicates a shrinking of the radial extension for the $J = 4$ state compared to lower levels.

3.2. Results on NGC 6946

The spiral galaxy NGC 6946 at $5.2\,\rm Mpc$ distance has been studied at various wavelengths. Up to now little is known about the molecular distribution in this galaxy because of the lack of extensive observations. The CO(1–0) map of Sofue et al. (1988) covered the central region only. The work of Casoli et al. (1990) added information about two regions in spiral arms $\pm 150''$ from the centre in the CO(1–0) and CO(2–1) transitions. Fig. 2 shows the spectra of the CO(4–3) emission smoothed to a resolution of $14\,\rm km/s$. In addition observations of the CO(3–2) transition by Dumke et al. (in prep.) at the same telescope are plotted as dashed lines. 19 positions at the centre of the galaxy and three positions in the outer spiral arms in regions of strong HI emission were observed. The observations at $180''/40''$ and $200''/20''$ offsets are situated on the inner edge of an optical spiral arm in the east of the galaxy, which also shows $\rm H_\alpha$ emission within the beams of our CO observations. The third position was placed in the western part in a star-forming region. In the first of these

Table 2. FWHP size of the central peak in NGC 6946

Line	Apparent width[1] [″]	Beam [″]	Deconvolved size[2] [″]	[pc]
CO(4–3)	26/23(2)	17	19/16(2)	500/450(50)
CO(3–2)	34/32(2)	22	26/23(2)	720/620(50)
CO(1–0)[3]	40/29(4)	17	36/24(4)	1030/620(90)

[1] The two values separated by a slash give the FWHP corresponding to the major and minor axis of the two-dimensional gaussian. The fitted position angles of the major axis are $0°$, $20°$ and $40°$. The errors are given in parentheses.
[2] The sizes are corrected for the galaxy's inclination.
[3] For the CO(1–0) transition these calculations are based on the spectra published by Sofue et al. (1988).

spectra there is a 5 σ detection at a distance of $3'$ away from the nucleus, corresponding to a deprojected galactocentric distance of $\cong 5\,\mathrm{kpc}$.

Up to now it was not expected to find molecular gas of high temperature and density so far from the centre of an external galaxy. At the moment it is too early to draw any conclusion on the physical conditions from the detection or non-detection in the different regions in the spiral arms. Presumably the emission arises from a small part of our beam.

We have made a comparison between the integrated line intensity of the CO(4–3) and CO(3–2) transition after a correction for the different beams. Again we find a slight decrease in the line ratio $R_{4,3}$ from 0.26 ± 0.05 in the centre to 0.21 ± 0.05 at $400\,\mathrm{pc}$ radius. Therefore we have studied the extension of the emission in NGC 6946 at the two transitions. The CO(4–3) intensity falls off much faster. Fitting a two-dimensional gaussian through the integrated spectra, we find extensions of $26''$ by $23''$ along the major and minor axis, respectively. The position angle was calculated to be $0°$. For the lower transition these values are $34''$ and $32''$ ($PA \sim 20°$, the uncertainty of the gaussians fitting is $\cong 2''$). Now we can deconvolve the apparent widths with the beams of $17''$ and $22''$ and get the sizes of the sources (see Table 2). Using the spectra published by Sofue et al. (1988) we have also calculated these numbers for the CO(1–0) transition. Here the deconvolved source size is $36''$ by $24''$ with a position angle of $40°$. Though this angle differs from the one for the higher transitions, we can state that in the direction of $PA = 90°$ the radial extension of the integrated CO emission is nearly the same for $J = 1$ and $J = 3$. For the $J = 4$ transition however, we find the emission significantly more concentrated to the centre of the galaxy, which was also suggested by the decrease in the line ratio. Thus we conclude that the physical conditions of density and temperature of the molecular gas are above the critical values to excite the $J = 3$ level, but CO(4–3) needs special conditions that are restricted to regions like the centre of the galaxy or local warm cores.

4. Discussion

The present observations open new possibilities of molecular studies of galaxies. The ability to map many CO line transitions (and their isotopic species) will allow us to narrow down the parameter space of temperature, density and optical depth in the context of e. g. Large Velocity Gradient analysis (see e. g. de Jong et al. 1975).

Here we report that the size of the central emission region of NGC 6946 decreases towards higher line transitions. A similar effect was found by Mauersberger et al. (1996) for the nucleus of NGC 4945. The slight decrease of the line ratio $R_{4,3}$ in the centre of the two galaxies shows that the excitation temperature is going down. This effect may be due to a variation of the kinetic temperature of the molecular gas as well as due to a change of the optical depth. We can state that the central molecular clouds have different physical conditions than the outer ones.

Furthermore, detection of the CO(4–3) line emission away from the centre, in the spiral arms of galaxies, has not been reported before. In view of the fact that mm and sub-mm bolometric observations of galaxies suggest the presence of cold dust ($T \sim 15\,\mathrm{K}$) in the spiral arms we must investigate why the kinetic temperatures of the molecular gas are around $40\,\mathrm{K}$ (LVG). Possibly even warmer cores can be found by high angular resolution interferometric observations. Data on more objects of different morphological type are also required to advance this subject. In any case, mapping of larger parts of the galaxies and also observing different isotopes are necessary to improve our studies and to use the LVG model to calculate the physical conditions of the molecular gas in galaxies.

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