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Extended warm CO gas in three nearby galaxies*

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Abstract. We report the detection of distributed CO(3–2) line emission in nearby normal galaxies. The CO gas is a well-known tracer of physical conditions in the emitting regions. The line transitions from higher energy levels (the J=3 level is 33 K above ground) are indicators of the presence of warm and dense gas. Until now this warm gas has been studied only in the nuclei of starburst galaxies. Using the Heinrich Hertz Telescope on Mt. Graham we were able to detect extended CO(3–2) line emission in more than ten normal galaxies. In this paper we present the results for the three galaxies M51, NGC 278 and NGC 4631. In particular, we compare our results with observations of the lower CO line transitions made with radio telescopes of similar angular resolution.

Key words: line: profiles – molecular data – ISM: molecules – galaxies: individual: M 51, NGC 278, NGC 4631 – galaxies: ISM

1. Introduction

CO gas is a tracer of molecular hydrogen observable at mm and sub-mm wavelengths. This is valid for molecular clouds in the Galaxy but also for extragalactic objects. In observations of galaxies, when the beamwidth subtends many molecular clouds at a time, care is needed to interpret the results. The intensity of the various line transitions can give us information about the local density, temperature and optical depth (e.g. Scoville & Solomon 1974; de Jong et al. 1975; Rohlfs & Wilson 1996). These possibilities have been used extensively by observers, especially in the framework of the Large Velocity Gradient (LVG) approximation and Monte-Carlo simulations. Additional information, which helps to interpret the physical situation in the clouds, has come from the various isotopomers of CO which observers have studied in addition to the ^{12}CO observations. One general fact of all these studies emerges: the higher line transitions are indicators of warmer and denser gas.

Extensive observations of the CO(1–0) line and the CO(2–1) line have been made in hundreds of galaxies (e.g. Braine et al. 1993; Young et al. 1995; Bajaja et al. 1995). Some nearby galaxies have also been mapped in the ^{13}CO transition (e.g. Loiseau et al. 1988; Harrison et al. 1999). The data on the CO(3–2) line transition is rather sparse in view of the lack of suitable telescopes on good sites to map the extended galaxies.

The first detection of the CO(3–2) line in the nearby starburst galaxy IC342 was reported by Ho et al. (1987). A few years later maps of the central regions of IC342 (Steppe et al. 1990) and of the core of M82 (Tilanus et al. 1991) were published. A report on CO(3–2) line intensities at 22 positions in the inner part of M51 was presented by Bash et al. (1990). In the multi-line studies of M51 some CO(3–2) observations were reported by Garcia-Burillo et al. (1993). Since then a couple of – mainly starburst – galaxies were observed in the CO(3–2) line, but they cover basically only the central regions of these objects (e.g. Devereux et al. 1994; Wilson et al. 1997; Petitpas & Wilson 1998; Harrison et al. 1999). Also the central positions were studied recently in the CO(3–2) line in 30 nearby galaxies by Mauersberger et al. (1999), also using the HHT. A CO(3–2) map of the central region of NGC 4945 was published by Mauersberger et al. (1996), claiming that the higher line transitions are concentrated to the nucleus. In this paper we present a discussion on multi-line studies of the three galaxies M51, NGC 278 and NGC 4631, suggesting that the warm and dense CO gas is rather extended in these objects.

2. Observations

We have used the 10-m Heinrich Hertz Telescope (e.g. Baars & Martin 1996) on Mt. Graham, Arizona between 1st and 18th April 1998 during medium weather conditions. A second observing session was available between 3rd and 17th December 1998. Several periods of clear weather ($0.05 < \tau_{225\mathrm{GHz}} < 0.15$) were available with the MPIfR two-channel 345 GHz SIS receiver. As backends we used the 1 GHz bandwidth 1024-channel Acousto-Optical Spectrometers supplied by the MPIfR which gives us a spectral resolution of 0.417 km s^{-1}. Receiver temperatures were between 120 K and 220 K (DSB) depending on the observing frequency. The system noise temperatures ranged from 400 K and up to 2000 K depending on weather and

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* Based on observations with the Heinrich-Hertz-Telescope (HHT). The HHT is operated by the Submillimeter Telescope Observatory on behalf of Steward Observatory and the MPI für Radioastronomie.

source elevation. The use of a double sideband receiver complicated our calibration procedures. However, as will be discussed later, good agreement has been found with several other published CO(3–2) observations made with other telescopes, so that we feel confident to quote main beam temperatures $T_{\rm mb}$ with an accuracy of better than 20%.

We have observed our galaxies with integration times of typically two minutes on-source, two minutes off-source. In April 1998 larger telescope movements from a low elevation planet to a galaxy gave pointing errors up to $10''$ peak to peak which could be overcome by mapping each galaxy. By using maps of 5×5 points we could overlap the different coverages. The relative pointing errors within a map of a galaxy were better than $3''$ peak to peak. In December 1998, after the replacement of an encoder cable, the pointing stability of the HHT was vastly improved. Moving the telescope from one planet to another, many degrees away in the sky, gave positional differences of $2''$ peak to peak in good ($\tau_{\rm 225GHz} < 0.08$) weather conditions. These positional accuracies could be furthermore maintained over many hours, allowing us to give an absolute positional accuracy of less than $3''$. In medium weather conditions ($0.08 < \tau_{\rm 225GHz} < 0.15$) the pointing would degenerate to some $5''$ peak to peak, still good enough for 345 GHz observations.

The beamwidth for CO(3–2) varied between $22''$ and $24''$ (FWHP) depending on the observing frequency. To achieve full sampling with this beamwidth we have used a $10''$ mapping grid. Since only a double sideband receiver was available we placed the CO line in the lower sideband, thus ensuring that we had no line in the upper band. We used the wobbling secondary reflector with a beam throw between $\pm 90''$ and $\pm 180''$, depending on the galaxy size and its orientation on the sky during observations.

We have observed the galaxies M82 and IC342 regularly which we used for a check of calibration consistency and pointing stability. The normal calibration was achieved by the insertion of a warm and cold (liquid nitrogen) load in the beam waist (where the beam emerges from the last mirror reflection, in front of the SIS receiver). Furthermore we have observed Galactic line calibrators as well. In particular, we have observed the stars χ Cyg and V Cyg and used the flux values given by Stanek et al. (1995) at 345 GHz. These observations have in particular confirmed the value of 0.5 for the main beam efficiency of the HHT which was used by the SMTO staff. We have also intercompared the data of Mauersberger et al. (1999) with our data for calibration. The agreement with this data set was very good. The line intensity values published by Bash et al. (1990) for the galaxy M51 made with the CSO telescope agree with our values to within 15%. In addition, we know that the HHT has a surface accuracy of $\sim 12\,\mu$ (B. Peters, private communication) which means that we do not expect problems in the calibration due to the error beam. In particular, we do not expect to have problems with emission in the sidelobes which will allow us to state that the CO(3–2) is indeed quite extended.

Taking all these factors into account and wanting to be on the conservative side, we estimate the absolute calibration accuracy to be better than 20%, which is consistent with variations commonly observed at sub-mm wavelengths. The relative accuracy within our maps is much better. We give our results here in main beam temperatures, $T_{\rm mb}$, which are connected to antenna temperatures by the same calibration scheme as used at the 30-m telescope, $T_{\rm mb} = (F_{\rm eff}/B_{\rm eff}) \times T_{\rm A}^*$, with $B_{\rm eff} \sim 0.5$ (see above) and $F_{\rm eff} \sim 1$ (D. Muders, priv. comm.).

In this paper we present the maps for the three galaxies M51, NGC 278 and NGC 4631. The CO(3–2) spectra of M51 are shown in Fig. 1. The extent of the mapped region is some $200'' \times 250''$ which is a considerable part of the well-known optical image of this galaxy. In addition, we have made a scan of $\pm 120''$ along the minor axis of M51. Extended CO(3–2) gas has been found in M51 in all positions where until now CO(2–1) and CO(1–0) line emissions were shown to be present by Garcia-Burillo et al. (1993) and Nakai et al. (1994). The CO(3–2) spectra for NGC 278 are shown in Fig. 2. The spectra show line emission in most of the $80'' \times 80''$ field. The galaxy NGC 278 has an optical extent of only $\sim 2'$ so that the CO(3–2) emission is present across most of this galaxy. The CO(3–2) spectra of NGC 4631 are shown in Fig. 3. These spectra again are present in the regions where lower frequency observations (Sofue et al. 1989; Golla & Wielebinski 1994) showed CO(1–0) and CO(2–1) line emissions.

3. Results

3.1. Results for M51

The galaxy M51 is classified as SA(s)bc pec (in RC2) and has an optical diameter $D_{25} = 10\rlap{.}'69$. The CO(3–2) spectra for M51 shown in Fig. 1 have been smoothed to 20 km s^{-1} and can best be compared with the spectra of CO(2–1) given in Garcia-Burillo et al. (1993). The comparison of the shapes of the spectra and their widths shows that they do not vary significantly, neither in the nucleus, nor in the spiral arms. The spectra (Fig. 1) were transformed into an integrated [K km s^{-1}] contour plot shown in Fig. 4. This plot shows a striking similarity to the colour plot of the CO(2–1) distribution published in Garcia-Burillo et al. (1993). There is also great similarity with the CO(1–0) map in Nakai et al. (1994). Since the CO(3–2) transition is expected to originate in warmer gas, the immediate conclusion is that warm CO gas is extended in M51, a result which was not expected on the basis of the few published results so far.

In the report of Bash et al. (1990) a claim was made that at two positions near the nucleus of M51 the CO(3–2) intensity was in fact higher than the CO(1–0) one. Our calibration accuracy of better than 20% allows us to make significant conclusions about the line ratios. We have made comparisons of the integrated line intensity ratios by smoothing the CO(1–0) data of Nakai et al. (1994). For the central region we find the line ratio $[R_{3,1} = I_{\rm CO}(3-2)/I_{\rm CO}(1-0)]$ of $R_{3,1} = 0.5 \pm 0.2$. In the inner spiral arms of M51 the line ratios are higher, $R_{3,1} = 0.7 \pm 0.2$. There seems to be no variation in these ratios along the inner spiral arms. In the outermost spiral arms, however, the line ratio increases to $R_{3,1} = 1.2 \pm 0.35$. Determinations in ten positions made by Garcia-Burillo et al. (1993) for the CO(3–2)/(2–1) line ratios were $R_{3,2} = 1.1$ in the centre of M51 and $R_{3,2} = 0.7$ in the spiral arms. We consider these ratios to be consistent with our

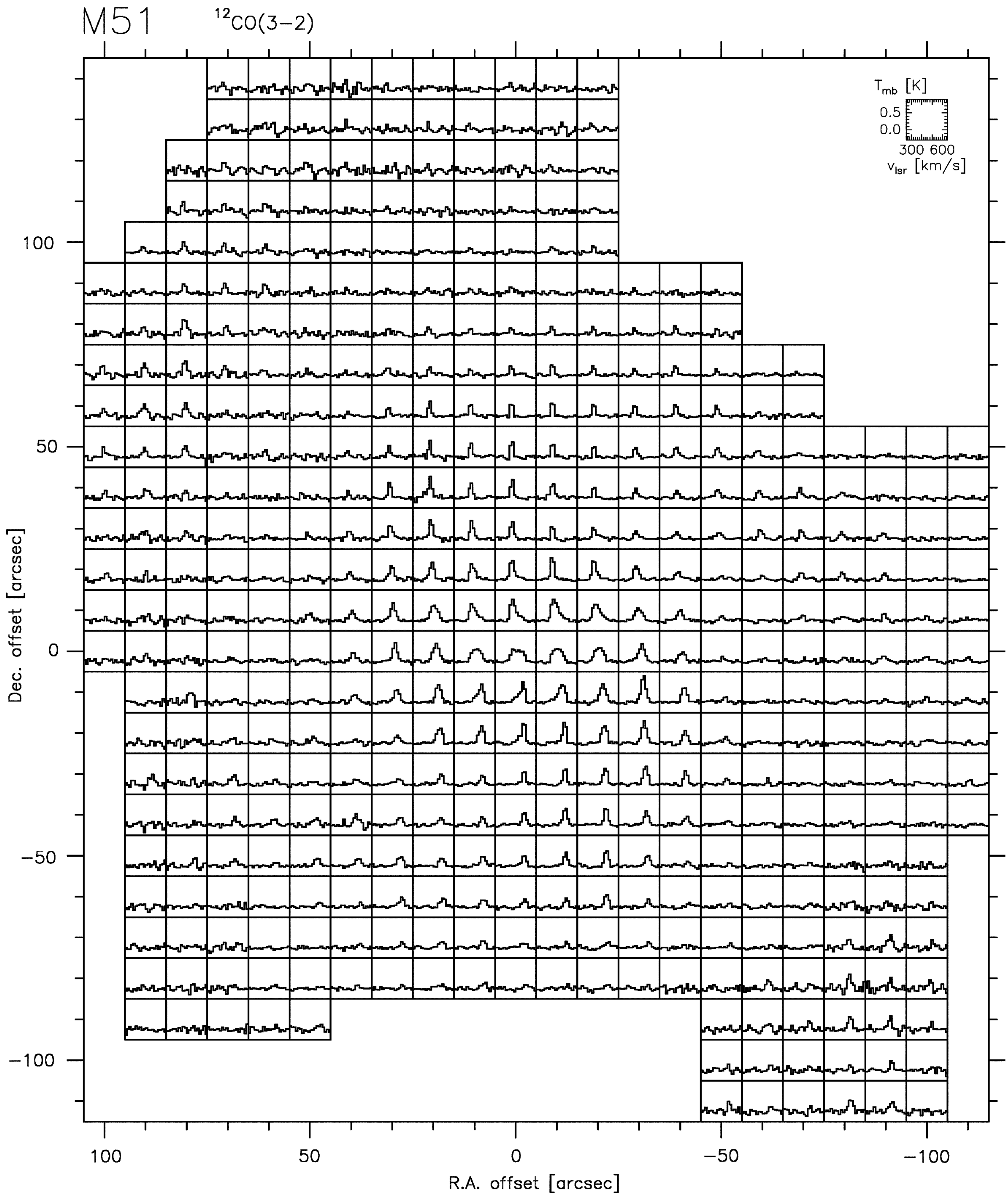

Fig. 1. The ^{12}CO(3–2) spectra in M51. Central position $\alpha_{50} = 13^{\rm h}27^{\rm m}46\farcs1$, $\delta_{50} = 47^\circ 27' 14''$

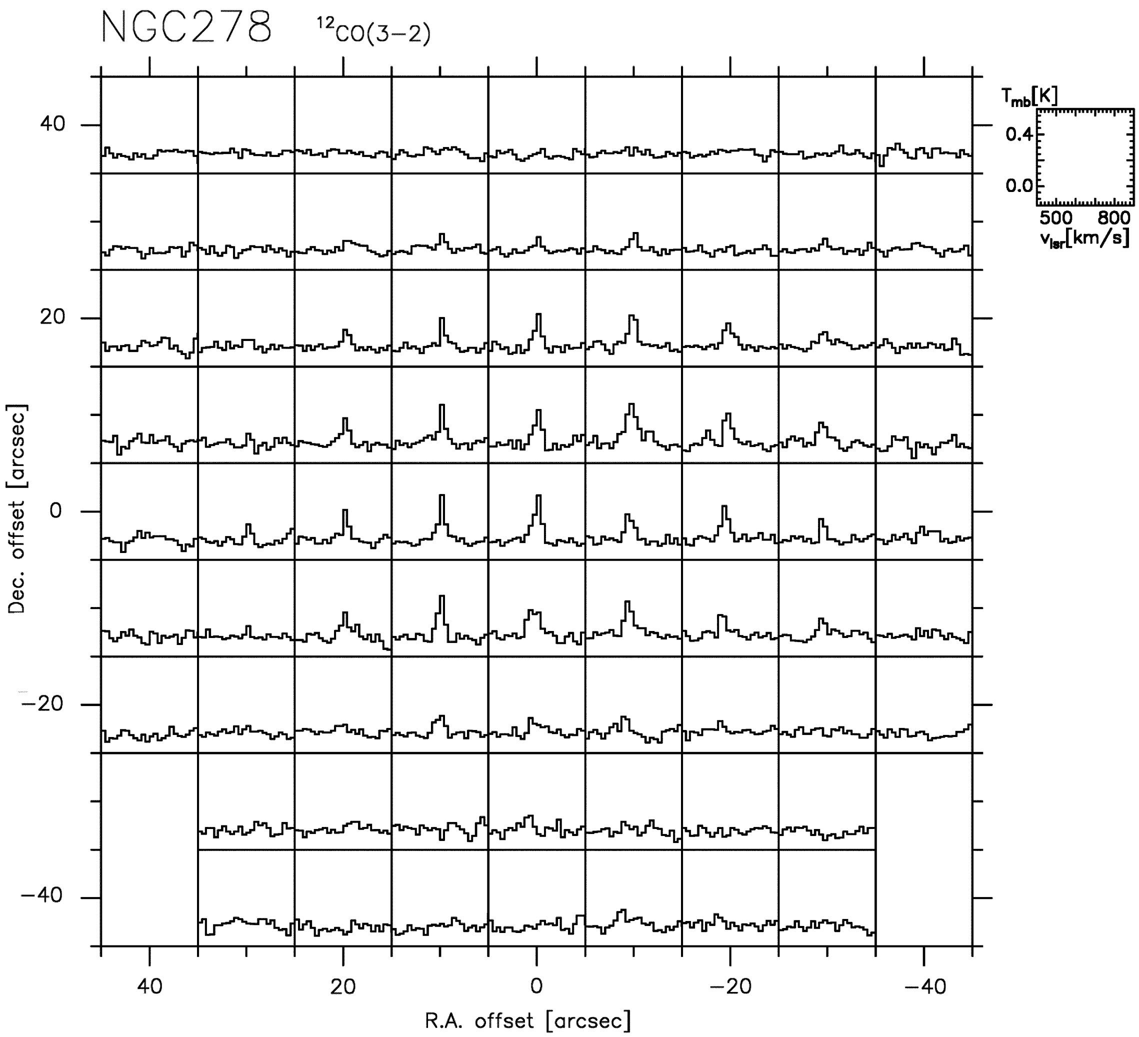

Fig. 2. The ^{12}CO(3–2) spectra in NGC 278. Central position $\alpha_{50} = 0^{\rm h}49^{\rm m}18\overset{s}{.}4$, $\delta_{50} = 47°16'43''$

determinations since 345 GHz Pico Veleta line intensity values could be underestimated because of the error beam which is present in the 30-m telescope observations.

3.2. Results for NGC 278

The galaxy NGC 278 is type SAB(rs)b with an optical diameter $D_{25} = 2\overset{'}{.}19$. The CO(3–2) spectra smoothed to 20 km s^{-1} shown in Fig. 2 are present across a large part of NGC 278. This observational fact immediately leads to the suggestion that the warm gas is widely distributed in this galaxy. The observations of Braine et al. (1993) suggested a line ratio $R_{2,1} \sim 1.0$. This high line ratio continues to our CO(3–2) observations. In fact relating the CO temperatures to the same beam area we get $R_{3,1} \sim 0.8 \pm 0.2$. Braine et al. (1993) claimed double structure of the central spectrum of NGC 278 which is suggested in our observations also, but slightly off the nucleus. A map of the CO(3–2) line emission suggests the existence of a ring-like structure, a fact that was discussed by Braine et al. (1993). Two spectra in the CO(1–0) line are published by Young et al. (1995) which also confirm the high line ratio after appropriate convolution. We note that the line width in NGC 278 is very narrow, possibly as narrow as 10 km s^{-1}, but similar at 115, 230, and 345 GHz. The study of NGC 278 by Schmidt et al. (1990) showed that the nucleus of this galaxy is dominated by young components. A recent starburst was suggested by the emission line spectrum presented in that paper. This would make NGC 278 more similar to M82 and not to M51. A more recent study of NGC 278 (Rhoads 1998) uses CO absorption at 2.3 μm to study the stellar content. This NIR study shows that the ring-like structure is seen in the optical range also.

3.3. Results for NGC 4631

The galaxy NGC 4631 is type SB(s)d sp seen edge-on with $D_{25} = 15\overset{'}{.}14$. The CO(3–2) spectra, again smoothed to 20 km s^{-1}, are shown in Fig. 3. The CO(1–0) data set for NGC 4631 can be found in Sofue et al. (1989) and in Golla & Wielebinski (1994). The CO(1–0) data in the Golla & Wielebinski paper have been collected simultaneously with the CO(2–1)

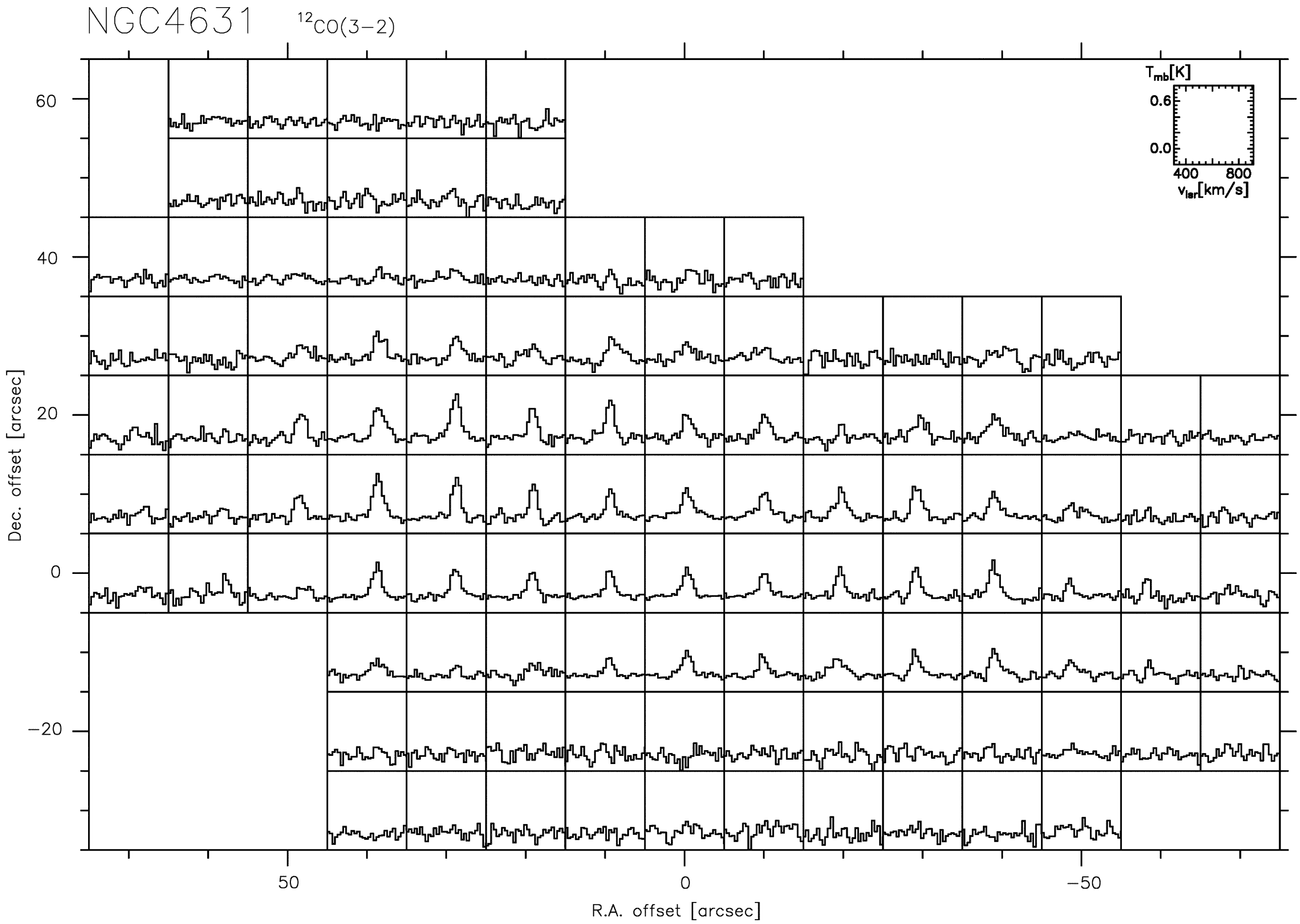

Fig. 3. The ^{12}CO(3–2) spectra in NGC 4631. Central position $\alpha_{50} = 12^{\rm h}39^{\rm m}41\farcs5$, $\delta_{50} = 32°48'54''$

data and hence on a grid of 6″. The comparison of the data sets gives $R_{3,1} \sim 1.2{\pm}0.2$ for the nuclear area and $R_{3,1} \sim 0.9{\pm}0.3$ for the regions of the CO maxima some $\pm 30''$ from the nucleus along the major axis. The published 'global' line ratio in Golla & Wielebinski (1994) is $R_{2,1} = 0.76 \pm 0.12$. We suggest that given the quoted calibration errors the line ratios are compatible. Certainly the line ratios are high for the "mild starburst" galaxy. We also see similar line widths at all positions in our respective maps. Some spectra were observed by Golla & Wielebinski (1994) along the major axis further out from the nucleus than in our present observations. We have used short integrations in our observations only and we have concentrated on the central area of NGC 4631.

4. Discussion

The three galaxies discussed in this paper are of quite different morphological types. However, the results that we have presented suggest that we have a warm, dense and widely distributed CO gas in all the three observed objects. The J=3 transition is 33 K above ground level. If the CO(3–2) lines were to be optically thick, temperatures of $T > 30$ K are expected to prevail in the emission regions. In the framework of a simple LVG analysis we expect the ratio $R_{3,1} \sim 1.0$ if the CO gas has $T_{\rm k} > 40$ K, $n_{\rm (H2)} > 3 \cdot 10^3$ cm^{-3}, and τ(J=1-0) < 1. For a more detailed computation of the possible values of the parameters for various velocity gradients we refer to Mauersberger et al. (1999). In the case that molecular clouds are sufficiently warm and dense, the opacity of the CO(3–2) line will be larger than that of the CO(1–0) line. In this case and if the excitation temperature of clump surfaces is larger than that in clump interiors, the CO(3–2) emission traces regions definitely warmer gas than the CO(1–0) line. This effect may bring the line ratio to be significantly larger than unity even when the emissions are opaque. Obviously, further supporting observations of other species (^{13}CO, C^{18}O etc.) are required to further the study of this interesting discovery. Additional observations of the CO(4–3) line at 460 GHz would also be very helpful. Also more accurate line ratios must be determined to differentiate between the various possible scenarios.

Although we have presented data for only three galaxies, we argue that surprisingly warm and dense CO gas is likely to be found in all nearby galaxies. The fact that the line intensity, line ratios and line widths are very similar in our three morphologically different galaxies indicates that similar heating

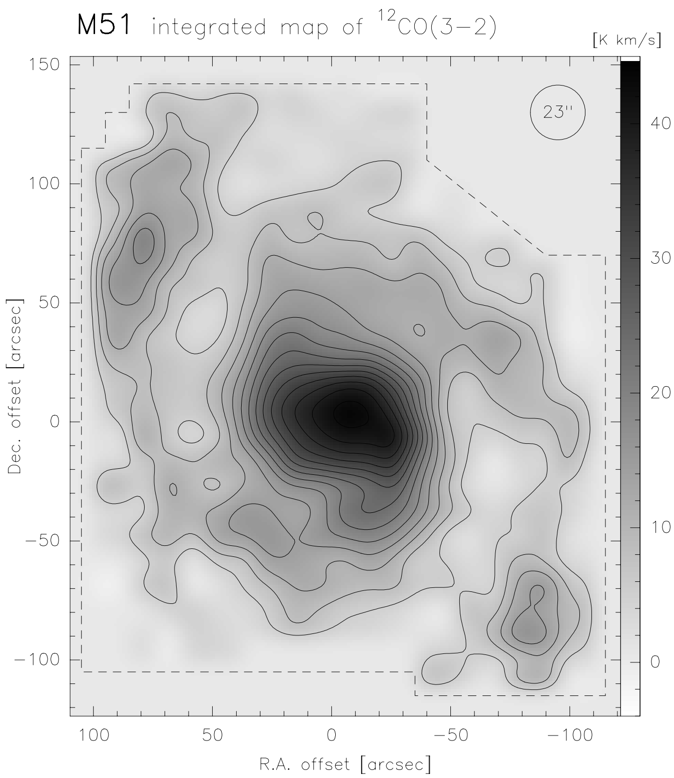

Fig. 4. The integrated distribution of CO(3–2) in M51. The contour lines indicate 3, 5, 7, ... times the r.m.s. noise ($\sigma_{\rm r.m.s.} = 1.6$ K km s^{-1})

mechanisms are at work. This would mean that quite high temperatures and densities must be present in the molecular clouds that fill only a small portion of our beam. In the recent paper by Mauersberger et al. (1999) this trend was shown to be present for the nuclei of many nearby galaxies.

The present observations of galaxies in the CO lines should also be considered in light of the measurements of dust temperatures using mm and sub-mm wavelength bolometers. In numerous studies of nearby galaxies the dust temperatures were found to have distinct components at two temperatures. The 1.2 mm continuum emission of NGC 4631, observed with a very similar telescope beam (Braine et al. 1995), gave temperature components of 20.5 K and 55 K. The decomposition of dust temperatures for M51 (Guélin et al. 1995) gave temperature components of 18 K and 50 K. The data from the ISO satellite (Hippelein et al. 1996) also suggest relatively high dust temperatures for the central region of M51. Our observations however suggest hotter CO gas to be present away from the nucleus of M51 in the outer spiral arms, where the dust temperatures are in fact lowest. Obviously detailed and more accurate line ratio determinations are required for the whole galaxies (as opposed to studies of nuclear regions only) to understand the situation in the galaxies.

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