CI and CO in nearby galaxy centers

The star-burst galaxies NGC 278, NGC 660, NGC 3628, NGC 4631, and NGC 4666

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ABSTRACT

Aims. We study the physical properties and mass of molecular gas in the central regions of galaxies with active nuclei.

Methods. Maps and measurements of the J = 1–0, J = 2–1, J = 3–2, J = 4–3 12CO, the J = 1–0, J = 2–1 and J = 3–2 13CO lines in the central arcminute squared of NGC 278, NGC 660, NGC 3628, NGC 4631, and NGC 4666, as well as 492 GHz [CI] maps in three of these are used to model the molecular gas.

Results. All five objects contain bright CO emission in the central regions. Clear central concentrations were found in NGC 660, NGC 3628, and NGC 4666, but not in the weakest CO emitters NGC 278 and NGC 4631. In all cases, the observed lines could be modeled only with at least two distinct gas components. The physical condition of the molecular gas is found to differ from galaxy to galaxy. Relatively tenuous (density 100–1000 cm$^{-3}$) and high kinetic temperature (100–150 K) gas occur in all galaxies, except perhaps NGC 3628, mixed with cooler (10–30 K) and denser (0.3–1.0 × 10$^4$ cm$^{-3}$) gas. The CO-to-H$_2$ conversion factor X is typically an order of magnitude less than the “standard” value in the Solar Neighborhood in all galaxy centers. The molecular gas is constrained within radii between 0.6 and 1.5 kpc from the nuclei. Within these radii, H$_2$ masses are typically 0.6–1.5 × 10$^8$ M$_\odot$, which corresponds to no more than a few per cent of the dynamical mass in the same region.

Key words. galaxies: ISM – submillimeter – galaxies: nuclei – galaxies: starburst – galaxies: spiral

1. Introduction

Molecular hydrogen (H$_2$) is a major constituent of the interstellar medium in late-type galaxies. Dense clouds of molecular gas are commonly found in the arms of spiral galaxies, but are frequently also concentrated in the inner few kiloparsecs. These concentrations of gas play an important role in the evolution of galaxy centers. They provide the material for the occurrence of inner galaxy star-bursts and the accretion of super-massive black holes in the nucleus. It is therefore important to determine their characteristics (density, temperature, excitation) and especially their mass but molecular hydrogen itself is very hard to observe directly. Instead, its properties are usually inferred from observations of tracer elements, notably the relatively abundant and easily excited CO molecule. Unfortunately, the CO emitting gas is not in LTE, and the most commonly observed 12CO lines are optically thick. We have to observe CO in various transitions to obtain reliable physical results and also in an optically thin isotope such as 13CO in order to break the temperature-density degeneracy that plagues 12CO intensities. The measured molecular (and atomic) line intensities are the essential input for modeling of the physical state of the gas.

We have observed a sample of nearby spiral galaxy centers in various CO transitions and in the 492 GHz $^3$P$_1$–$^3$P$_0$ [CI] transition. These galaxies were selected to be bright at infrared wavelengths, and more specifically to have IRAS flux densities $f_{12,\mu m}$ ≥ 1.0 Jy. The results for a dozen galaxies from this sample have already been published. These are NGC 253 (Israel et al. 1995), NGC 7331 (Israel & Baas 1999), NGC 6946 and M 83 = NGC 5236 (Israel & Baas 2001 – Paper I), IC 342 and Maffei 2 (Israel & Baas 2003 – Paper II), M 51 = NGC 5194 (Israel et al. 2006 – Paper III), NGC 1068, NGC 2146, NGC 3079, NGC 4826, and NGC 7469 (Israel 2009 – Paper IV). In this paper, we present the results obtained for five bright galaxies undergoing intense star formation (star-burst) in their inner parts. We have summarized basic observational parameters of these galaxies in Table 1.

Although the appearance of all five galaxies in this paper is completely dominated by a central star-burst, NGC 4666 and perhaps NGC 3628 also contain a very modest AGN. NGC 660 shows clear evidence for a recent merger event, and NGC 278 may also have experienced a recent (minor) merger. The other three galaxies, NGC 3628, NGC 4631, and NGC 4666, are all interacting with nearby companions. All five galaxies are at similar distances: three of them at about 12 Mpc, one (NGC 4631) somewhat closer at 8 Mpc, and one (NGC 4666) somewhat more distant at 23 Mpc. Thus, our best angular resolutions of 10$^6$–14$^"$ correspond to linear resolutions of typically 600–850 pc. This is not sufficient to reveal appreciable structural detail in the central CO distributions; millimeter array observations are required for that. However, the multi-transition observations of 12CO and 13CO presented here allow us to characterize the overall physical condition of the central molecular gas in ways not possible otherwise.

2. Sample galaxies

2.1. NGC 278 = DDO 9

This is an isolated, relatively small and almost face-on galaxy with a bright nucleus and multiple, spiral arms. Its optical size is about 2′ corresponding to a diameter of 7 kpc. However, in
HI its diameter is five times greater (Knapen et al. 2004). Its
dust-rich central parts are quite bright not only in the H$\alpha$ line,
but also in the infrared continuum (Dale et al. 2000; Sanders
et al. 2003) and the [CII] line (Malhotra et al. 2001) consistent
with intense star-forming activity (Ho et al. 1995; Eskridge et al.
2002). Optical images show a bright, compact nucleus, but there
is no indication for even a low-luminosity AGN (Tzanavaris
et al. 2003) and the [CII] line (Malhotra et al. 2001) consistent
but also in the infrared continuum (Dale et al. 2000; Sanders
et al. 2003) which is considerably greater than 6.7 Mpc often found in the
NGC 3623. In this paper, we adopt a distance of 11.9 Mpc,
the Leo Triplet (Arp 317) which also includes NGC 3627 and
23′′ (projected linear separation 190 pc). The apparent dimen-
sions of the radio source vary with beam-size, but a size of
25′′ × 12′′ (1500 × 800 pc) is a reasonable approximation. Flux
densities are $S_{1.4 \text{ GHz}} = 374 \text{ mJy}$, $S_{4.9 \text{ GHz}} = 156 \text{ mJy}$ for the ex-
tended source total whereas the peaks have $S_{4.9 \text{ GHz}} = 53$ and
41 mJy respectively. The radio continuous spectrum is domi-
nated by non-thermal emission but the relatively shallow spec-
trum ($\alpha = -0.6$) suggests a non-negligible amount of thermal
emission from this LINER galaxy. Indeed, high-density ionized
gas is implied by the H$\alpha$2 radio recombination line emission
detected by Phookun et al. (1998). High-frequency (15 GHz) ra-
dio continuum maps reveal several compact continuum sources
most likely large complexes of high-density star-forming regions
and a compact nuclear source is lacking at radio wavelengths

<table>
<thead>
<tr>
<th>NGC 278</th>
<th>NGC 660</th>
<th>NGC 3628</th>
<th>NGC 4631</th>
<th>NGC 4666</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type$^{a}$</td>
<td>SAB(rs)b</td>
<td>SB(s)a pec; HII/Liner</td>
<td>SAB pec sp Liner</td>
<td>SB(s)d</td>
</tr>
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<td>RA (B1950)$^{a}$</td>
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<td>00$^{h}$40$^{m}$21.7$^{s}$</td>
<td>11$^{h}$17$^{m}$40.3$^{s}$</td>
<td>12$^{h}$39$^{m}$41.9$^{s}$</td>
</tr>
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<td>+13$^{\circ}$23′37″</td>
<td>+13$^{\circ}$51′49″</td>
<td>+32$^{\circ}$48′56″</td>
</tr>
<tr>
<td>RA (2000)$^{a}$</td>
<td>00$^{h}$52′04.3$^{s}$</td>
<td>01$^{h}$43′02.4$^{s}$</td>
<td>11$^{h}$20′17.0$^{s}$</td>
<td>12$^{h}$42′08.0$^{s}$</td>
</tr>
<tr>
<td>Dec (2000)$^{a}$</td>
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<td>+13$^{\circ}$38′42″</td>
<td>+13$^{\circ}$35′23″</td>
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<td>$V_{LSR}$</td>
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<td>+841 km s$^{-1}$</td>
<td>+838 km s$^{-1}$</td>
<td>+618 km s$^{-1}$</td>
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<tr>
<td>Inclination$^{b}$</td>
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<td>70$^{\circ}$</td>
<td>87$^{\circ}$</td>
<td>86$^{\circ}$</td>
</tr>
<tr>
<td>Position angle$^{b}$</td>
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<td>45$^{\circ}$</td>
<td>102$^{\circ}$</td>
<td>86$^{\circ}$</td>
</tr>
<tr>
<td>Distance$^{c}$</td>
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<td>13.0 Mpc</td>
<td>11.9 Mpc</td>
<td>7.7 Mpc</td>
</tr>
<tr>
<td>Scale</td>
<td>58 pc/″</td>
<td>63 pc/″</td>
<td>58 pc/″</td>
<td>37 pc/″</td>
</tr>
</tbody>
</table>

Notes: $^{a}$ NED, $^{b}$ Nishiyama & Nakai. (2000); van Driel et al. (1995); Irwin & Sofue (1996); Rand (2000); Walter, et al. (2004), $^{c}$ Moustakas & Kennicutt (2006).

2.2. NGC 660

NGC 660 is a remarkable galaxy seen mostly edge-on but ex-
hibiting clear merger signs such as out-of-the-plane (“polar
ring”) tidal features and two intersecting dust lanes. It is one
of the two major members of the NGC 628 Group. Radio con-
tinuum maps (Condon, 1980; Condon et al. 1982, 1990) reveal
an extended radio source with two distinct peaks, separated by
3′ (projected linear separation 190 pc). The apparent dimen-
sions of the radio source vary with beam-size, but a size of
25′′ × 12′′ (1500 × 800 pc) is a reasonable approximation. Flux
densities are $S_{1.4 \text{ GHz}} = 374 \text{ mJy}$, $S_{4.9 \text{ GHz}} = 156 \text{ mJy}$ for the ex-
tended source total whereas the peaks have $S_{4.9 \text{ GHz}} = 53$ and
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nated by non-thermal emission but the relatively shallow spec-
trum ($\alpha = -0.6$) suggests a non-negligible amount of thermal
emission from this LINER galaxy. Indeed, high-density ionized
gas is implied by the H$\alpha$2 radio recombination line emission
detected by Phookun et al. (1998). High-frequency (15 GHz) ra-
dio continuum maps reveal several compact continuum sources
most likely large complexes of high-density star-forming regions
and a compact nuclear source is lacking at radio wavelengths

(Carral et al. 1990) nor is there any obvious X-ray counterpart to
the nucleus (Dudik et al. 2005). A detailed study of the galaxy,
including HI and $J = 1–0$, $J = 2–1$ 12CO mapping (Nobeyama,
17′, IRAM, 12′′) was carried out by Van Driel et al. (1995).

The authors concluded that NGC 660 is the result of a merger of
two equally massive objects a few billion years ago. Single dish
$J = 1–0$ 12CO measurements towards the center of NGC 660
have been summarized by Elfhag et al. (1996) and a $J = 1–0$
major axis map was presented by Young et al. (1995, FCRAO,
1′′). Aalto et al. (1995) measured 13CO and 12CO in the two
lower transitions but there appear to be no high-resolution array
maps of the CO emission in this galaxy. Strong absorption to-
wards the nucleus of NGC 660 has been detected in HI and in
OH by Baan et al. (1992), as well as in H$_2$CO (cf. Mangum et al.
2008). An outflow was identified by Baan et al. (1992).

2.3. NGC 3628

This is an edge-on Sbc galaxy and part of a close group called
the Leo Triplet (Arp 317) which also includes NGC 3627 and
NGC 3623. In this paper, we adopt a distance of 11.9 Mpc,
which is considerably greater than 6.7 Mpc often found in the
literature. Where appropriate, we have recalculated dimensions
quoted in other papers for the new distance value. NGC 3628
is a galaxy well-studied in various ways. Its highly disturbed
HI distribution betrays its interaction with NGC 3627
(Rots 1978; Haynes et al. 1979). Radio continuum observations
and Reuter et al. (1991) show an extended central radio core of
size 6′′×1′′ (350×60 pc) and flux density $S_{1.4 \text{ GHz}} = 0.2$ Jy with
a predominantly non-thermal spectrum ($\alpha = -0.86$). OH and HI
absorption observations led Schmelz et al. (1987a,b) to propose
the existence of a small, rapidly rotating circumnuclear disk with
an outer radius of 365 pc, i.e. nearly twice the size of the radio
continuous central disk. As in NGC 660, formaldehyde is seen in
absorption against the extended central radio continuum source
suggesting the presence of large masses of high-density molecu-
lar gas (Mangum et al. 2008, and references therein). Indeed,
the center of NGC 3628 resembles that of NGC 660 also by its
complement of compact radio continuum sources (none coincid-
ing with the nucleus) representing active regions in the cir-
cumnuclear star-burst contributing about 10% to the total radio
continuum emission (Carral et al. 1990), and by its H92α ra-
dio recombination line emission from high-density HI regions
($n_{\text{HI}} \approx 10^3 \text{ cm}^{-3}$ – Anantharamaih et al. 1993; Zhao et al.
1997). The central core of NGC 3628 is also bright in X-rays,
and the galaxy has an extended halo of soft X-ray emission
surrounding a central outflow, apparently a galactic (star-burst-driven) super-wind bubble (Dahlem et al. 1996, 1998; Strickland et al. 2004a,b; Grimes et al. 2005; Floci et al. 2006). NGC 3628 may (Roberts et al. 2001; González-Martín et al. 2006) or may not (Dudik et al. 2005) contain a low-luminosity AGN.

Single dish \( J = 1−0 \) \(^{12}\text{CO} \) observations have been reported by Rickard et al. (1982, NRAO, 55\(^{\prime}\)), Young et al. (1983, FCRAO, 45\(^{\prime}\)), and Braine et al. (1993, IRAM, 22\(^{\prime}\); \( J = 2−1, 12\(^{\prime}\), as well). Higher-resolution (10\(^{\prime}\)−20\(^{\prime}\)) \(^{12}\text{CO} \) maps were published by Boissé et al. (1987, IRAM, \( J = 1−0, 22\(^{\prime}\))

Israel et al. (1990, JCM T, \( J = 2−1, 21\(^{\prime}\))

Reuter et al. (1991, IRAM, \( J = 2−1, 12\(^{\prime}\))

major-axis maps of \(^{13}\text{CO} \) and \(^{12}\text{CO} \) in the \( J = 1−0 \) transition were presented by Pratine et al. (2001, FCRAO, 45\(^{\prime}\)). NGC 3628 was also mapped in the \( J = 1−0 \) \(^{12}\text{CO} \) transition at high resolutions (3.85\(^{\prime}\)) with the Nobeyama array (Irwin & Sofue 1996).

2.4. NGC 4631

NGC 4631 is an edge-on spiral galaxy interacting with another edge-on spiral neighbor, NGC 4656, and possibly also with the dwarf elliptical NGC 4627 (cf. Combes 1978). The distribution of H\( \text{I} \) throughout the group has been mapped by e.g. Welsher et al. (1978) and Rand (1994); the WSRT providing a 12\(^{\prime}\) beam very similar to the resolution of our CO measurements. Both total-intensity and major-axis-velocity maps show strong warping and corrugation of the galaxy disk. Notwithstanding its edge-on orientation, many star formation regions are seen in H\( \alpha \) and UV (Smith et al. 2001), both using the FCRAO telescope with a resolution of 3.85\(^{\prime}\). The major axis of NGC 4631 has been mapped in \(^{12}\text{CO} \) by Young et al. (1995; Paglione et al. (1995), both using the FCRAO telescope with a resolution of 3.85\(^{\prime}\), as well). The galaxy does have a non-thermal edge-on orientation, many star formation regions are seen in H\( \alpha \) with the observed radio structures suggests wind-driven outflow from a mild star-burst in the central 5 kpc of the disk (Wang et al. 2001; Strickland 2004a,b). However, the lack of a central concentration in star formation is remarkable. In this sense, NGC 4631 resembles NGC 278 more than the other galaxies in this paper.

The major axis of NGC 4631 has been mapped in \( J = 1−0 \) \(^{12}\text{CO} \) and \(^{13}\text{CO} \) by Young et al. (1995) and Paglione et al. (2001), both using the FCRAO telescope with a resolution of 45\(^{\prime}\), and in the \( J = 2−1 \) \(^{12}\text{CO} \) transition by Sofue et al. (1990, IRAM, 13\(^{\prime}\)). The galaxy was fully mapped in the \( J = 1−0 \) and \( J = 2−1 \) transitions of \(^{12}\text{CO} \) by Golla & Wielebinski (1994, IRAM, 22\(^{\prime}\) and 12\(^{\prime}\)). They published the first detailed maps of \(^{12}\text{CO} \) at five different positions in the same transition. They found that CO emission extends over 7\(^{\prime}\) (15 kpc) along the plane of NGC 4631, but mostly occur within a diameter of 2\(^{\prime}\) (4.5 kpc), corresponding to the star-burst region delineated in radio and X-ray emission. However, CO is not concentrated to the center. A map of NGC 4631 in \( J = 3−2 \) \(^{12}\text{CO} \) was published by Dumke et al. (2001), who also noted the similarities between NGC 278 and NGC 4631. Finally, the inner 10\(^{\prime}\) (3700 pc) of the galaxy were mapped at high resolution in \( J = 1−0 \) \(^{12}\text{CO} \) by Rand (2000, BIMA, 10\(^{\prime}\) \( \times \) 7\(^{\prime}\)), who identified a molecular component in the outflow from the center as well as extended CO structure in the disk itself.

2.5. NGC 4666

The IRAS survey revealed the highly tilted Sc galaxy NGC 4666 to be an infrared-luminous star-forming galaxy part of a small group of galaxies also containing NGC 4668 and NGC 4632 (Garcić 1993; see also Walter et al. 2004). In the last decade or so, the galaxy has been observed frequently as part of various surveys, but few detailed studies exist. In the first of these, Dahlem et al. (1997) found that the central 5.5 kpc (reduced to our adopted distance of 22.6 Mpc) of NGC 4666 is the host of a star-burst from which a galactic super-wind flows out into an extended halo. Star-burst, outflow and halo can be identified in X-rays (Dahlem et al. 1997, 1998; Persic et al. 2004). In addition to a star-burst, NGC 4666 also hosts a modest AGN (Persic et al. 2004; Dudik et al. 2005). NGC 4666 thus presents an appearance similar to that of the much closer NGC 3079 (see Israel 2009, and references therein). Low resolution (VLA) radio continuum maps have been presented by Condon (1983), Condon et al. (1990), and Dahlem et al. (1997) who found integrated flux-densities of about 0.16 Jy at 4.9 GHz and 0.40 Jy at 1.5 GHz. No nuclear (point source) flux density has been determined so far; from Condon et al. (1990) an upper limit is \( S_{\text{1.5}} \leq 0.17 \) Jy must be assumed. A major-axis map of NGC 4666 in \( J = 1−0 \) \(^{12}\text{CO} \) was published by Young et al. (1995, FCRAO, 45\(^{\prime}\)). Maps in H\( \alpha \) and in the \( J = 1−0 \) \(^{12}\text{CO} \) (SEST: 45\(^{\prime}\), IRAM 21\(^{\prime}\), OVRO 4\(^{\prime}\) \( \times \) 3\(^{\prime}\)) as well as the \( J = 2−1 \) \(^{12}\text{CO} \) (IRAM: 11\(^{\prime}\)) were published by Walter et al. (2004). These authors found direct evidence for interactions within the group, probably causing the star-burst in NGC 4666.

3. Observations and reduction

The observations described in this paper were carried out with the 15 m James Clerk Maxwell Telescope (JCMT) on Mauna Kea (Hawaii)\(^{1} \) and with the IRAM 30 m telescope in Pico Veleta (Spain)\(^{2} \).

3.1. JCMT observations

At the epoch of the mapping observations (1991–2001) the absolute pointing of the telescope was good to about 3\(^{\prime}\) rms as provided by pointing observations with the JCMT sub-millimeter bolometer. The spectra were calibrated in units of antenna temperature \( T_{A} \), correcting for sideband gains, atmospheric emission in both sidebands and telescope efficiency. Calibration was regularly checked by observation of a standard line source. Further observational details are given in Tables 2 and 3. Most of the observations were carried out with the new defunct receivers A2, B3i and C2. Observations in 2001 were obtained with the newer receivers B3 (330/345 GHz) and W/C (461 GHz). Full details on these receivers can be found at the JCMT website (http://docs.jach.hawaii.edu/JCMT/HET/GUIDE/). Up to 1993, we used a 2048-channel AOS back-end covering a band of 500 MHz (650 km s\(^{-1}\) at 230 GHz).

\(^{1} \) The James Clerk Maxwell Telescope is operated on a joint basis between the United Kingdom Particle Physics and Astrophysics Council (PPARC), the Netherlands Organisation for Scientific Research (NWO) and the National Research Council of Canada (NRC).

\(^{2} \) The IRAM 30 m telescope is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).
Observations of both $^{12}\text{CO}$ and $^{13}\text{CO}$ in the $J = 1–0$ and $J = 2–1$ transitions at resolutions of 21″ and 12″ respectively were obtained towards the centers of all galaxies with the IRAM 30 m telescope in the period 2005–2007. We used the IRAM facility low-noise receivers A and B in both the 3 mm and the 1 mm bands. For back-ends we used the 1 MHz and 4 MHz filter banks, as well as the VESPA correlator. Initially, all four transitions were observed simultaneously, therefore with identical banks, as well as the VESPA correlator. Initially, all four transitions were observed simultaneously, therefore with identical banks, as well as the VESPA correlator.

All maps were made in rectangular grids (parameters given in Table 2), rotated to parallel the major axis of the galaxy mapped. The maps shown in this paper all have been rotated back to a regular grid in right ascension and declination.

### 3.1.1. IRAM observations

Observations of both $^{12}\text{CO}$ and $^{13}\text{CO}$ in the $J = 1–0$ and $J = 2–1$ transitions at resolutions of 21″ and 12″ respectively were obtained towards the centers of all galaxies with the IRAM 30 m telescope in the period 2005–2007. We used the IRAM facility low-noise receivers A and B in both the 3 mm and the 1 mm bands. For back-ends we used the 1 MHz and 4 MHz filter banks, as well as the VESPA correlator. Initially, all four transitions were observed simultaneously, therefore with identical banks. After this, the signal-to-noise ratio of the $^{13}\text{CO}$ profiles was increased by additional simultaneous observation of the two transitions, where we took care to ensure that the pointing was the same as for the earlier observations. Calibration and reduction procedures were standard and similar to those described in the previous section. The assumed $\eta_{\text{mb}}$ values are likewise given in Tables 2 and 3. The IRAM observations were especially important not only because they provide measurements of the 3 mm $J = 1–0$ transitions not possible with the JCMT. IRAM aperture is twice that of the JCMT, so that the combination of the two data sets provides $J = -1/J = 1–0$ and $J = 3–2/J = 2–1$ ratios in closely-matched beams.

#### 3.2. Results

Central line profiles in all observed transitions are shown in Figs. 1 through 5. We mapped the distribution of the molecular gas in the galaxy centers in the $J = 2–1$, $J = 3–2$, and $J = 4–3$ transitions, typically over an area of about one arcminute across. These maps are also shown in the figures, as are the major-axis position-velocity diagrams of the central CO emission.

Measured line intensities towards the center of each galaxy are listed in Table 4. This Table contains entries both at full resolution, and at resolutions corresponding to those of transitions observed in larger beams. These entries were extracted from maps convolved to the resolution quoted. The convolution was carried out with the map interpolation function of the SPECX data reduction package. This function interpolates, where necessary, the map intensities by using adjacent pixels out to a preset distance (usually 2 beams) and convolved the observed and interpolated data points with a two-dimensional Gaussian function ("beam") of predetermined half-width. This half-width is chosen such that the actual observing beam convolved with the 2D-Gaussian would yield a beam corresponding to the desired resolution. Velocities in a position-velocity map can also be "smoothed" by applying a convolving Gaussian function in a similar manner.

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**Table 2. $^{12}\text{CO}$ observations Log.**

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Date</th>
<th>$T_{\text{sys}}$ (K)</th>
<th>Beam size (″)</th>
<th>$\eta_{\text{mb}}$</th>
<th>t(int) (s)</th>
<th>Map parameters</th>
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<tr>
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<td></td>
<td></td>
<td>600</td>
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<tr>
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<td></td>
<td>1200</td>
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<tr>
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<td></td>
<td>780</td>
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<tr>
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<td></td>
<td></td>
<td>840</td>
<td>1 – – –</td>
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<tr>
<td>NGC 278</td>
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<td>0.53</td>
<td>960</td>
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<tr>
<td></td>
<td>91Nov,01Sep</td>
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<td>21</td>
<td>0.69</td>
<td>600/300</td>
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<td>0.69</td>
<td>300/600</td>
<td>30</td>
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<td>NGC 3628</td>
<td>05Oct.</td>
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<td>NGC 4631</td>
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<td>0.53</td>
<td>780</td>
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<td>0.70</td>
<td>400/300</td>
<td>53</td>
<td>120 x 40 10 84</td>
</tr>
<tr>
<td>NGC 4666</td>
<td>06Jul.</td>
<td>224</td>
<td>12</td>
<td>0.53</td>
<td>840</td>
<td>1 – – –</td>
</tr>
<tr>
<td></td>
<td>00Dec,01Nov</td>
<td>1104/325</td>
<td>21</td>
<td>0.69</td>
<td>300/480</td>
<td>70 60 x 130 10 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 278</td>
<td>00Jul,01Jan</td>
<td>625/440</td>
<td>14</td>
<td>0.63</td>
<td>240/480</td>
<td>45 50 x 50 8 0</td>
</tr>
<tr>
<td>NGC 660</td>
<td>95Jul,00Jul</td>
<td>1039/701</td>
<td></td>
<td>0.61</td>
<td>960/1080</td>
<td>29 30 x 70 10 51</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>94Apr,94Nov</td>
<td>534/870</td>
<td></td>
<td>0.58</td>
<td>240/400</td>
<td>50 120 x 40 8 105</td>
</tr>
<tr>
<td>NGC 4631</td>
<td>01Nov.</td>
<td>485</td>
<td></td>
<td>0.63</td>
<td>240</td>
<td>47 80 x 40 8 84</td>
</tr>
<tr>
<td>NGC 4666</td>
<td>00Feb,00Jul</td>
<td>517/441</td>
<td></td>
<td>0.63</td>
<td>900/2700</td>
<td>48 70 x 70 6 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 278</td>
<td>01Jan.</td>
<td>1370</td>
<td>11</td>
<td>0.53</td>
<td>600</td>
<td>11 12 x 18 6 0</td>
</tr>
<tr>
<td>NGC 660</td>
<td>99Aug</td>
<td>3900</td>
<td></td>
<td>0.53</td>
<td>2400</td>
<td>8 18 x 18 6 51</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>94Apr.</td>
<td>2716</td>
<td></td>
<td>0.50</td>
<td>720</td>
<td>15 36 x 24 6 105</td>
</tr>
<tr>
<td>NGC 4631</td>
<td>96Apr.</td>
<td>1679</td>
<td></td>
<td>0.50</td>
<td>2400</td>
<td>5 24 x 24 6 86</td>
</tr>
<tr>
<td>NGC 4666</td>
<td>01Nov.</td>
<td>2785</td>
<td></td>
<td>0.52</td>
<td>1440</td>
<td>13 24 x 24 6 0</td>
</tr>
</tbody>
</table>

---

By comparing observed and model intensities, we may identify the physical parameters best describing the actual conditions at the observed positions. Beam-averaged properties are determined by comparing observed and model intensities. In principle, with seven measured line intensities of two isotopes, properties of a single gas component are overdetermined as only five independent observables are required. In practice, this is mitigated by degeneracies such as occur for 12CO. In any case, we find that fits based on a single-component gas are almost always incapable of fully matching the data.

Finally, we have determined the line intensity ratios of the observed transitions at the center of the galaxies observed. They have been determined independently from the intensities given in Table 4. Specifically: (a) we used data taken at the same observing run wherever possible, (b) we determined ratios at various resolutions convolving the maps to the relevant beam widths, and (c) we verified ratios by comparing profile shapes in addition to integrated intensities. In Table 5, whenever data were insufficient for convolution, or altogether lacking (e.g. [CI]), no entry is provided.

### 4. Analysis

#### 4.1. Radiative transfer modelling of CO

We have modeled the observed 12CO and 13CO line intensities and ratios with the large-velocity gradient (LVG) radiative transfer models described by Jansen (1995) and Jansen et al. (1994) – but see also Hogerheijde & van der Tak (2000) and the web page http://www.strw.leidenuniv.nl/~michiel/ratran/. These codes provide model line intensities as a function of three input parameters per molecular gas component: gas kinetic temperature $T_k$, molecular hydrogen density $n(H_2)$ and the CO column density per unit velocity $N(CO)/dV$. Full details of the relevant molecular and atomic line data used in these models can be found in Schöier et al. (2005). By comparing model to observed line ratios, we may identify the physical parameters best describing the actual conditions at the observed positions. Beam-averaged properties are determined by comparing observed and model intensities. In principle, with seven measured line intensities of two isotopes, properties of a two-component gas model gas is only an approximation.
of reality but it is decidedly superior to one-component model solutions. As long as significant fractions of the total molecular gas mass are limited to similar segments of parameter space, they also provide a reasonably realistic model for the actual state of affairs. Specifically, our analysis is less sensitive to the occurrence of gas at very high densities and temperatures, but such gas is unlikely to contribute significantly to the total mass.

In order to reduce the number of free parameters, we assumed identical CO isotopic abundances for both gas components. Furthermore, in a small number of star-burst galaxy centers (NGC 253, NGC 4945, M 82, IC 342, He 2-10), values of 40 ± 10 have been suggested for the isotopic abundance [12CO]/[13CO] (Mauersberger & Henkel 1993; Henkel et al. 1993, 1994, 1998; Bayet et al. 2004), somewhat higher than the characteristic value of 20–25 for the Milky Way nuclear region (Wilson & Rood 1994). We therefore have adopted an abundance value of [12CO]/[13CO] = 40 in our models. We identified acceptable fits by searching a grid of model parameter combinations (10 K ≤ T_k ≤ 150 K, 10^2 cm^{-3} ≤ n(H_2) ≤ 10^5 cm^{-3}, 6 × 10^{15} cm^{-2} ≤ N(CO)/dV ≤ 3 × 10^{18} cm^{-2}) for model line ratios matching the observed set, with the relative contribution of the two components as a free parameter. The models rarely predict the precise set of line ratios that is observed. The 12CO ratios are generally derived from observations taken at different times, and require convolution of one of the lines to the resolution of the other. In contrast, 12CO/13CO line ratios are derived from observations done (quasi)simultaneously and in with identical beams, so that they are much more accurately determined. Thus, when confronted with competing sets of model ratios in which one or more of the individual ratios differs from the observed ratio beyond the observational uncertainty, we value a good fit to the 12CO transition ratios much less than one to the observed 12CO/13CO line ratios. Comparison of the entries in Table 5 and the last six columns of Table 6 shows that this choice had to be made for NGC 3628 (in particular for the J = 4−3/J = 2−1 ratio, and also for NGC 4631 which is difficult to fit with any model set.

Solutions obtained in this way are not unique, but rather define a limited range of values in distinct regions of parameter space. For instance, variations in input parameters may to some extent compensate one another, producing identical line
The results of our model fitting procedure are summarized in Table 6. The table lists, under the proviso just given, representative model solutions reproducing the observed line ratios. In appropriate cases (e.g. N 278, N 660, and N 3628), two solutions are given, each representative of a group of solutions with very similar parameters. No galaxy observation set yielded more than two groups of plausible solutions. The Table gives for each of the two representative gas components the kinetic temperature $T_{\text{kin}}$, the H$_2$ volume density $n_{\text{H}_2}$, and the CO gradient $N(\text{CO})_d$. The relative contribution of the two components to the observed $J = 2-1$ $^{12}$CO emission is also given. The last six columns give the corresponding model ratios, which may be compared directly to the observed ratios (in a 21″ beam) in Table 5.

4.2. Beam-averaged molecular gas properties

Chemical models, such as presented those by van Dishoeck & Black (1988) and recently updated by Visser et al. (2009), show a strong dependence of the (neutral and ionized) atomic carbon to carbon monoxide column density ratio, $N(\text{C})/N(\text{CO})$, on the total carbon $N_C = N(\text{C}) + N(\text{CO})$ and molecular hydrogen column densities. With line intensities $I_{\text{CO}}$, $I_{\text{[CI]}}$, and $I_{\text{[CII]}}$ of all three species known, minimal assumptions suffice to deduce total carbon and hydrogen column densities and masses.

Unfortunately, when we have incomplete or no knowledge of these C$^+$ and C$^+$ line intensities, as is the case here and often elsewhere as well, this procedure is useless. However, lacking direct and full atomic carbon information, we may still make progress by using a new element instead. The total [Cl]/[H] gas-phase carbon abundance may serve equally well as a constraining factor in addition to the CO column density resulting from the radiative transfer model. The chemical models provide the fraction of CO (i.e. the ratio of carbon monoxide to atomic carbon, whether neutral or ionized) as a function of H$_2$ column density. The fraction derived from the models varies as a function of H$_2$ volume density and the radiation field. In all cases we used the H$_2$ density derived from the LVG modeling. For the average radiation field, we assumed relatively moderate conditions to apply...
Table 4. Measured central $^{12}$CO and $^{13}$CO line intensities.

<table>
<thead>
<tr>
<th>Beam size (arcsec)</th>
<th>NGC 278</th>
<th>NGC 660</th>
<th>NGC 3628</th>
<th>NGC 4631</th>
<th>NGC 4666</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J = 1−0$</td>
<td>22 595 21 ± 2</td>
<td>635 163 ± 16</td>
<td>980 211 ± 25</td>
<td>550 45 ± 6</td>
<td>395 77 ± 9</td>
</tr>
<tr>
<td>$J = 2−1$</td>
<td>12 755 26 ± 3</td>
<td>1377 352 ± 35</td>
<td>1420 207 ± 25</td>
<td>600 45 ± 6</td>
<td>505 74 ± 9</td>
</tr>
<tr>
<td>$J = 3−2$</td>
<td>21 393 16 ± 2</td>
<td>516 137 ± 14</td>
<td>710 151 ± 18</td>
<td>390 263 ± 3</td>
<td>320 54 ± 6</td>
</tr>
<tr>
<td>$J = 4−3$</td>
<td>14 414 15 ± 2</td>
<td>490 164 ± 19</td>
<td>860 163 ± 20</td>
<td>280 223 ± 3</td>
<td>315 51 ± 6</td>
</tr>
<tr>
<td>$J = 5−4$</td>
<td>11 310 15 ± 2</td>
<td>565 161 ± 16</td>
<td>930 176 ± 21</td>
<td>250 192 ± 2</td>
<td>150 28 ± 5</td>
</tr>
</tbody>
</table>

Table 5. Adopted velocity-integrated line ratios in galaxy centres.

<table>
<thead>
<tr>
<th>Transitions</th>
<th>Beam (arcsec)</th>
<th>NGC 278</th>
<th>NGC 660</th>
<th>NGC 3628</th>
<th>NGC 4631</th>
<th>NGC 4666</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$CO</td>
<td>(1–0)/(2–1)</td>
<td>21 0.89 ± 0.16</td>
<td>1.19 ± 0.17</td>
<td>1.40 ± 0.28</td>
<td>1.72 ± 0.26</td>
<td>1.42 ± 0.21</td>
</tr>
<tr>
<td>(2–1)/(3–2)</td>
<td>12/21 1.58 ± 0.24</td>
<td>2.57 ± 0.40</td>
<td>1.38 ± 0.28</td>
<td>1.68 ± 0.25</td>
<td>1.37 ± 0.21</td>
<td></td>
</tr>
<tr>
<td>(3–2)/(4–3)</td>
<td>21 0.79 ± 0.13</td>
<td>0.69 ± 0.11</td>
<td>0.62 ± 0.12</td>
<td>0.66 ± 0.10</td>
<td>0.69 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>(4–3)/(5–4)</td>
<td>12 0.74 ± 0.13</td>
<td>0.66 ± 0.12</td>
<td>0.87 ± 0.17</td>
<td>0.58 ± 0.09</td>
<td>0.80 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>(5–4)/(6–5)</td>
<td>21 0.56 ± 0.08</td>
<td>0.66 ± 0.11</td>
<td>0.65 ± 0.13</td>
<td>—</td>
<td>0.30 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>(6–5)/(7–6)</td>
<td>12 0.54 ± 0.10</td>
<td>0.49 ± 0.09</td>
<td>0.74 ± 0.15</td>
<td>0.46 ± 0.07</td>
<td>0.36 ± 0.05</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Radiative transfer model parameters.

<table>
<thead>
<tr>
<th>No.</th>
<th>Kin. temp. $T_k$ (K)</th>
<th>Gas dens. $n(H_2)$ ($cm^{-3}$)</th>
<th>Gradient $N(CO)/dV$</th>
<th>Kin. temp. $T_k$ (K)</th>
<th>Gas dens. $n(H_2)$ ($cm^{-3}$)</th>
<th>Gradient $N(CO)/dV$</th>
<th>Emiss. ratio Comp. 1:2</th>
<th>$^{12}$CO/(1–0)/(2–1)</th>
<th>Model ratios $^{12}$CO/(1–0)/(2–1)</th>
<th>$^{12}$CO/13CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 500 10 × 10^{17} 30</td>
<td>100 000 0.3 × 10^{17}</td>
<td>3:17</td>
<td>0.92 0.79 0.52</td>
<td>8.0 8.9 11.0</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2</td>
<td>150 30 30 × 10^{17} 30</td>
<td>100 000 0.3 × 10^{17}</td>
<td>1:4</td>
<td>0.94 0.80 0.53</td>
<td>8.2 9.2 11.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>150 500 0.6 × 10^{17} 20</td>
<td>100 000 0.3 × 10^{17}</td>
<td>11:9</td>
<td>1.17 0.75 0.49</td>
<td>15.8 11.8 12.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>150 100 0.6 × 10^{17} 150</td>
<td>3000 1.0 × 10^{17}</td>
<td>4:1</td>
<td>1.17 0.72 0.50</td>
<td>16.3 12.3 12.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>150 1000 3.0 × 10^{17} 20</td>
<td>100 000 0.3 × 10^{17}</td>
<td>1:9</td>
<td>1.10 0.74 0.43</td>
<td>12.8 12.2 8.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>20 100 1.0 × 10^{17} 30</td>
<td>100 000 0.6 × 10^{17}</td>
<td>17:3</td>
<td>1.32 0.63 0.47</td>
<td>12.4 12.3 8.7</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>150 1000 1.0 × 10^{17} 10</td>
<td>300 0.45 × 10^{17}</td>
<td>1:5</td>
<td>1.52 0.65 0.42</td>
<td>13.5 10.5 13.2</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>100 1000 1.0 × 10^{17} 10</td>
<td>100 000 0.6 × 10^{17}</td>
<td>7:13</td>
<td>1.32 0.70 0.37</td>
<td>8.5 6.7 11.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

to the objects studied here, e.g. radiation field intensities typically about an order of magnitude higher than those in the Solar Neighborhood, or less. At the same time, the gas phase carbon abundance provides us with the total carbon column (i.e. the sum of carbon monoxide and atomic carbon) for any H2 column density. Thus, each value of $N(H_2)$ is associated with a unique value of $N(C)/N(CO)$ and a unique value of $N_C = N(C) + N(CO)$. Knowing any one of the three column densities (e.g. $N(CO)$, the two equations allow us to find the remaining columns (e.g. $N(H_2)$ and $N(C)$). What fraction of all atomic carbon (C) is ionized ($C^+$) or neutral ($C^0$) remains undetermined, but that does not concern us here.
Oxygen abundances and gradients of many nearby galaxies have been compiled by Vila-Costas & Edmunds (1992), Zaritsky et al. (1994), and Pilyugin et al. (2004). None of the five galaxies studied here is included in any of these compilations. The first two compilations suggest nuclear metallicities many times solar, but Pilyugin et al.’s more recent work implies nuclear metallicities on average only 1.5 times solar. A major uncertainty in these values is caused by the extrapolation of disk HII region abundances to the very different galaxy center environment.

We have conservatively assumed a metallicity twice solar for the galaxy central regions. The results published by Garnett et al. (1999) suggest very similar carbon and oxygen abundances at these metallicities, so that we adjust [C]/[H] = 1.0 × 10^{-3}. As a significant fraction of carbon is tied up in dust particles and thus unavailable in the gas-phase, we have also adopted a fractional correction factor δ_C = 0.27 (see for instance van Dishoeck & Black 1988), so that N(H)/N(C) = [2N(H_2) + N(HII)]/[M(CO) + N(CII) + N(CI)] = 3700, uncertain by about a factor of two. In Table 7 we present beam-averaged column densities for CO and C (=C+ + C^+) as well as H_2 derived under these assumptions. As the observed peak CO intensities are significantly below the model peak intensities, only a small fraction of the (large) beam surface area can be filled with emitting material.

Although the analysis in terms of two gas components is superior to that assuming a single component, it is not fully realistic. For instance, the assumption of e.g. identical beam filling factors for the various species (^{12}CO, ^{13}CO, C^+, and C^+) is not a priori plausible. However, as argued before (cf. Israel 2009), the beam-averaged column-density is modified only by the degree of non-linearity in the response of the model parameters to a change in filling factor, not by the magnitude of that change. A similar state of affairs exists with respect to model degeneracy. Even for rather different model fractions of hot or dense gas, in any particular galaxy the beam-averaged molecular hydrogen densities are practically the same. The uncertainties introduced by plausibly different average radiation fields are also relatively minor. As we are observing with a large linear beamsize, we are not sensitive to the very highly excited or very dense molecular gas that only occurs on small scales. In fact, the assumed gas-phase carbon abundance dominates the results.

The derived beam-averaged column-densities (and projected mass densities) roughly scale self-similarly proportional to the square root of the abundance assumed: N_{CO} \propto [C]/[H]^{0.5}

As our estimate of the central elemental carbon abundance, and our estimate of the carbon depletion factor are unlikely to be wrong by more than a factor of two, the resulting uncertainty in the final values listed in Table 7 should be no more than 50%.

5. Discussion

5.1. NGC 278

The CO distribution shown in Fig. 1 reveals that there is no concentration of molecular gas towards the nucleus of the galaxy, as was already suggested by the lower-resolution map of Dumke et al. (2001). Instead, a few local peaks in the extended diffuse emission occur near positions of enhanced radio continuum emission in the spiral arms (see Condon 1986).

This is particularly clear in a map of peak rather than integrated brightness temperature (see Fig. 6), showing unresolved maxima with T_{mb} = 0.5–0.7 K. These CO and radio continuum peaks mark the locations of major star-forming complexes in the inner disk. The molecular gas in the SE arm appears to be somewhat warmer than that in the NW arm. The inner rotation gradient in Fig. 1 is 150 km s^{-1}/kpc. Taking into account distance and inclination of the galaxy as listed in Table 1, this corresponds to 90 km s^{-1} kpc^{-1}. The maximum rotational velocity width is 110 km s^{-1}, or 235 km s^{-1} corrected for inclination. In the center of the galaxy, the slow decrease of ^{12}CO intensity with increasing rotational transition (Table 6) suggests the presence of a fair amount of warm molecular gas. At the same time, the ^{13}CO/^{12}CO isotope intensity ratios are not particularly high, implying that reasonably dense gas should also be present. Indeed, a robust result of our modeling (Tables 6, 7) is that almost 90 per cent of the molecular gas mass is relatively dense (n_H = 10^{11} cm^{-3}) and not very warm with a kinetic temperature of about 30 K. The remaining 10 per cent of the molecular mass is much hotter (T_K = 100–150 K) and much less dense (n_H = 100–500 cm^{-3}). Such temperatures and densities are not unusual for photon-dominated regions (PDRs) associated with the star formation process. Notwithstanding the uncertainty in the hot component parameters, the beam-averaged parameters allow for very little variation. Most of the carbon should be in CO, the ratio of C to CO being 0.4.

The implied face-on molecular hydrogen mass density of 8 M_S/pc^2 is not exceptional. The relatively low beam-averaged molecular hydrogen column density N(H_2) = 6 \times 10^{20} cm^{-2} combined with the modest J = 1-0 ^{12}CO intensity of 21 K km s^{-1} implies a low value for the CO-to- H_2 conversion factor X = 3 \times 10^{-16} cm^2/K km s^{-1}, i.e. typically 6–7 times less than the Solar Neighbourhood conversion factor. Again, this is not unusual and in line with findings for other galaxies (cf. the discussion in Israel 2009).

5.2. NGC 660

As Fig. 2 shows, there is a clear CO maximum spanning the central (deconvolved) 17'', which means that there is a very significant molecular gas concentration within a radius R = 500 pc from the nucleus. At lower levels of surface brightness, CO emission is present over the full extent of our maps. Indeed, in the (IRAM 30 m) ^{12}CO maps published by Van Driel et al. (1995), ever weaker emission is seen to extend out to radii of 70'' (4.4 kpc). The central CO emission peak in NGC 660 is quite strong (Table 4). The major-axis/velocity diagram suggests...
that this central molecular gas is in rapid rotation, following a solid-body rotation curve. The velocity gradient of rotation is 355 km s$^{-1}$ kpc$^{-1}$, corrected for inclination; the full rotational width is 450 km s$^{-1}$, again corrected for inclination. In Figs. 2 and 7, the very central few arcseconds (corresponding to a radius $R \leq 100$ pc) show a pronounced molecular gas minimum. The size of this minimum corresponds closely to the separation of the radio peaks mentioned earlier. The $^{12}$CO ratios in Table 5 suggest that the gas within a radius of 6$''$ ($R \leq 380$ pc) is both cooler (lower $^{12}$CO (4–3)/(2–1) ratio) and less optically thick (higher $J \geq 2$–$1$ $^{12}$CO/$^{13}$CO ratio) than that between radii of 11$''$ and 6$''$ ($R = 380–700$ pc). More in general, the observed line ratios may be explained by either of two models. The corresponding reasonably good fits (see Table 6) are virtually indistinguishable notwithstanding the differences in underlying physical conditions. Tables 6 and 7 show that in the first model, two thirds of the gas mass is hot ($T_{\text{kin}} = 150$ K) and tenuous ($n_{H_2} \approx 500$ cm$^{-3}$), and the remaining third is cold ($T_{\text{kin}} = 20$ K) and very dense ($n_{H_2} \approx 10^5$ cm$^{-3}$). In the second model, essentially all gas is hot ($T_{\text{kin}} = 150$ K), three quarters is very tenuous ($n_{H_2} \approx 100$ cm$^{-3}$) and the remaining quarter is only modestly dense ($n_{H_2} \approx 300$ cm$^{-3}$). Overall, the two models lead to integrated central masses and projected mass densities different by a factor two, the latter model yielding the highest values. As either of the two solutions yields plausible parameters, it is not easy to determine which model is the more likely to apply. We may nevertheless firmly conclude that in the center of NGC 660 most of the molecular gas is very hot and rather tenuous. The corresponding CO-to $H_2$ conversion factor in the center of is $X = 0.8 \pm 1.6 \times 10^{19}$ cm$^{-2}$ K km s$^{-1}$, i.e. 12–25 times lower than the “standard” Solar Neighborhood value. We find that the implied central gas mass is 1–2% of the dynamical mass in the same volume.

5.3. NGC 3628

Figure 3 shows bright CO emission from the galaxy, strongly concentrated in the inner 30$''$ (i.e. within radii $R \leq 850$ pc). The overall extent suggested by our $J = 3$–$2$ $^{12}$CO single-dish measurements is in excellent agreement with the size shown in the $J = 1$–$0$ $^{12}$CO array map by Irwin & Sofue (1996). The major-axis velocity diagram shows two kinematic components. A fast-rotating feature in the center extends over only half this size. It is superposed on molecular gas in more leisurely rotation extending over the full area mapped in CO. The extent of the fast-rotating component is the same as that of the OH/HI absorption feature measured by Schmelz et al. (1987a,b). The velocity gradient of rotation is 360 km s$^{-1}$ kpc$^{-1}$, corrected for inclination – very similar to that of NGC 660, but the full rotational width of 305 km s$^{-1}$ (again corrected for inclination) is much less than that of NGC 660. The molecular gas distribution in Figs. 3 and 8 does not exhibit an obvious central minimum such as most other galaxies do but we cannot rule out that the limited spatial resolution and the steep velocity gradient conspire to hide a small central minimum. The IRAM $J = 2$–$1$ $^{12}$CO maps by Reuter et al. (1991) suggest that this is indeed the case. The fact that the radio core is about half the size of the extent of the

Table 7. Beam-averaged model parameters.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Beam-averaged column densities</th>
<th>Outer</th>
<th>Central</th>
<th>Face-on</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N$(CO) ($10^{15}$ cm$^{-2}$)</td>
<td>radius</td>
<td>$H_2$ mass</td>
<td>mass density</td>
</tr>
<tr>
<td></td>
<td>$N$(C) ($10^{18}$ cm$^{-2}$)</td>
<td>$R$ (kpc)</td>
<td>$M_{H_2}$ ($10^8$ $M_\odot$)</td>
<td>$\sigma(H_2)$ ($M_\odot$ pc$^{-2}$)</td>
</tr>
<tr>
<td>NGC 278</td>
<td>1/2 0.24 0.09 0.6 0.9 0.6 7 0.90:0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 660</td>
<td>3 0.33 0.38 1.3 0.9 1.2 15 0.67:0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 3628</td>
<td>4 0.49 0.96 2.7 0.9 1.2 — 0.55:0.45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 4631</td>
<td>5 2.7 0.13 5.2 0.6 1.5 — 0.25:0.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 4666</td>
<td>6 2.1 0.65 5.1 0.6 1.5 — 0.90:0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7. Center of NGC 660, $J = 4$–$3$ $^{12}$CO position-velocity map in position angle PA = 45$^\circ$ integrated over a strip 14$''$ wide with contours in steps of 40 mK; northeast is at top.

Fig. 8. Center of NGC 3628. Top: (Left) $J = 4$–$3$ $^{12}$CO emission integrated over the velocity interval 650–1050 km s$^{-1}$; contour step is 40 K km s$^{-1}$; (right) [CI] emission integrated over the same velocity interval; contour step is 5 K km s$^{-1}$, lowest contour is at 20 K km s$^{-1}$. Bottom: $J = 4$–$3$ $^{13}$CO position-velocity map in position angle PA = 105$^\circ$ integrated over a strip 20$''$ wide with contours in steps of 10 mK; east is at top.
molecular gas in the fast-rotating component suggests that much of the star-burst takes place at the inside of this molecular gas concentration. Throughout the central region, we have observed emission from neutral carbon. However, the very center shows an unresolved (i.e. diameter less than 250 pc) [CI] peak (Fig. 8).

The line ratios in Table 5 suggest that the observed molecular gas is only modestly optically thick. Comparison of the ratios in a 21′′ beam with those in a 12′′ beam implies that the molecular gas in the central region close to the radio core (marking the star-burst) is denser or warmer than the gas at slightly greater (R = 350–600 pc) distances to the nucleus. We suspect that the former is the dominant effect, because almost all the molecular gas in the center of NGC 3628 is relatively cold: all model fits, including those shown in Table 6, solidly suggest predominant temperatures \( T_{\text{kin}} = 20–30 \) K. In model 5, most of the gas is both cool and dense \( (n_H_2 = 10^4 \, \text{cm}^{-3}) \), but there is a non-negligible mass of hot \( (T_{\text{kin}} = 150 \, \text{K}) \) and less dense \( (n_H_2 = 10^3 \, \text{cm}^{-3}) \) gas. In model 6, all of the gas is cool, and most of it is rather tenuous \( (n_H_2 = 10^2 \, \text{cm}^{-3}) \).

In this model, there is only a small mass of cool gas at higher densities \( (n_H_2 = 10^4 \, \text{cm}^{-3}) \). Given the star-burst nature of NGC 3628, model 5 appears physically more plausible, as is also suggested by the presence of warm dust in NGC 3628 (Rice et al. 1988). In terms of beam-averaged quantities, the difference between the two models is slight. In model 5 almost all \( (95\%) \) of all carbon is in CO. In model 6 this fraction is somewhat lower \((75\%)\). Both have beam-averaged \( H_2 \) column densities \( N_{H_2} \approx 5 \times 10^{21} \, \text{cm}^{-2} \) which is very similar to the peak HI column density listed by Braun et al. (2007). These column densities are relatively high but this is not surprising given the edge-on orientation of the galaxy. Because of this, we could not reliably estimate the face-on mass-density. The central molecular gas mass is \( M_{H_2} = 1.5 \times 10^3 \, M_\odot \) within \( R = 0.6 \, \text{kpc} \), independent of the model assumed. Towards the center of NGC 3628, the CO-to \( H_2 \) conversion factor is \( X = 2.4 \times 10^{19} \, \text{cm}^{-2} \, \text{K} \, \text{km} \, \text{s}^{-1} \), i.e. 8 times lower than the “standard” Solar Neighborhood value. A roughly similar value was also estimated by IRwin & Sofue (1996). The molecular mass in the central region calculated by us is typically 2–6% of the dynamical mass.

5.4. NGC 4631

The CO maps in Fig. 4 are more detailed than those published earlier by Golla & Wielebinski (1994) and Dunke et al. (2001), but similar overall aspect. The maps published by these authors show that the most intense CO emission ranges from \( \Delta \alpha = +60' \) to \( \Delta \alpha = -40' \) in our map which just covers this range. CO intensities are at a relative minimum at the position of the nucleus of the galaxy, which is located not at the map \((0, 0)\) position, but offsets \( \Delta \alpha = +12.5', \Delta \delta = -6' \). In the integrated intensity maps, nor in the major axis-velocity map is there any sign of molecular gas associated with the nucleus, a conclusion we share with Rand (2001). In addition, the velocity-integrated CO brightness temperatures are much lower in NGC 4631 (and NGC 278) than in galaxies with distinct central CO concentrations such as, for instance, NGC 660 and NGC 3628. There are, however, several unresolved CO intensity peaks at various distances to the midplane of the galaxy. These might be thought to reflect spiral arm tangential locations but this is not very probable because they are not placed symmetrically with respect to the nucleus. More likely they are instead giant molecular cloud complexes hosting the burst of star formation that is taking place in the central region of NGC 4631. In support of this, we note that they tend to coincide with radio continuum peaks in the map by Golla (1999), while the easternmost and brightest CO peak also corresponds to the Hα emission region CM 67 (Crillon & Monnet 1969). The peak CO brightness temperatures in Fig. 9 are \( T_{\text{mb}} = 0.5–0.8 \, \text{K} \). These are almost identical to the brightness temperatures found for similar CO peaks in NGC 278 and suggest filling factors of the order of 0.02–0.05 when compared with Galactic GMC’s of typical size 100–150 pc. If we could view NGC 4631 face-on, it would probably much resemble NGC 278. Contrary to earlier interpretations, we do not find the observed CO structure of NGC 4631 to suggest the presence of ring- or bar-like structures in the galaxy.

The line ratios of the diffuse gas in the line of sight through the center of NGC 4631 (Table 5) do not allow much choice in model parameters. Twenty per cent of the gas mass sampled in this direction is warm \( (T_{\text{kin}} \approx 150 \, \text{K}) \) and moderately dense \( (n_H_2 \approx 1000 \, \text{cm}^{-3}) \) but most \((80\%)\) of it is cold \( (T_{\text{kin}} \approx 10 \, \text{K}) \) and relatively tenuous \( (n_H_2 \approx 300 \, \text{cm}^{-3}) \). In this particular direction which does not sample an active center nor an actively star forming region, beam-averaged \( H_2 \) column densities are not particularly high (cf. Table 7) and most \((70\%)\) of the carbon appears to be in atomic form. Towards the center of NGC 4631 we find a CO-to \( H_2 \) conversion factor \( X = 3.1 \times 10^{19} \, \text{cm}^{-2} \, \text{K} \, \text{km} \, \text{s}^{-1} \), i.e. 6 times lower than the “standard” Solar Neighborhood value. Paglione et al. (2001) estimated an X-factor only slightly higher than this towards the center of NGC 4631. Thus, the implied molecular gas mass in NGC 4631 is much lower, and a much smaller fraction of the dynamical mass, than use of the “standard” conversion factor would suggest.

5.5. NGC 4666

The maps in Fig. 5 show CO emission to extend over 120′′ (13 kpc) in the plane of the galaxy. This extent only marginally exceeds that of the CO emission mapped at high resolution by Walter et al. (2004, their Fig. 8). The \( ^{12}\text{CO} \) maps show a strong central peak, which we also observed in the \( J = 4–3 \) transition (Fig. 10). Although the slightly asymmetrical CO distribution in our \( J = 3–2 \) \( ^{12}\text{CO} \) position-velocity map suggests a small offset from the nucleus, this central CO peak is in fact coincident with the kinematic center of the galaxy derived from the H I emission by Walter et al. (2004). Nevertheless, their CO array maps show that the central molecular gas maximum seen in our maps in the lower \( J \) transitions is, in fact, a blend of a compact CO maximum centered on the nucleus and star-forming molecular clouds in the disk close to the nucleus. The compact appearance of the central
condensation in the $J = 4 - 3$ $^{12}$CO map (Fig. 10) implies that it is significantly denser than the gas farther from the nucleus.

The inner parts of NGC 4666 rotate fast, with an inclination-corrected velocity span of 360 km s$^{-1}$ over the central arcminute. Unlike most of the other galaxies mapped by us, the inner parts of NGC 4666 do not quite follow a solid-body rotation curve.

We note that the $^{12}$CO/$^{13}$CO ratios of NGC 4666 are relatively low and similar to those of NGC 278. As is the case in that galaxy, such values suggest the relatively high CO optical depths characteristic of star-forming Giant Molecular Clouds in the Milky Way disk. Our model analysis in Tables 6 and 7 yields roughly equal masses of modestly dense ($n_{H_2} \approx 10^3$ cm$^{-3}$) and hot ($T_{kin} \approx 100$ K) gas and dense ($n_{H_2} \approx 10^5$ cm$^{-3}$) and cold ($T_{kin} \approx 10$ K) gas. There are roughly equal masses of neutral carbon and carbon monoxide. Molecular hydrogen column densities, central mass, and face-on mass density do not stand out with respect to the other galaxies discussed in this paper. The central CO-to-$H_2$ conversion factor implied by Tables 4 and 7 is only $X \approx 1.4 \times 10^{19}$ cm$^{-2}$/K km s$^{-1}$, a factor 14 lower than the Solar Neighborhood standard. The central mass is about 0.5 per cent of the dynamical mass.

5.6. Column densities and masses

For the galaxies in this paper, we find $H_2$ column densities averaged over a 21″ beam of roughly 0.5–5 × $10^{21}$ cm$^{-2}$ (corresponding to total hydrogen columns of 1–10 × $10^{21}$ cm$^{-2}$). Thus, these galaxies cover a somewhat greater range than the 2–6 × $10^{21}$ cm$^{-2}$ that we found for more active galaxies in our previous paper (Israel 2009) and they are mostly somewhat lower. These total columns also include the ambient contribution by neutral atomic hydrogen which we have so far neglected. Previously, we have found that HI absorption column densities actually measured usually exceed the beam-averaged $H_2$ column densities we derive. This is also the case for the only two galaxies with HI absorption results in the literature, NGC 660 (Baan et al. 1992) and NGC 3628 (Schmelz et al. 1987a), with typical HI absorption column densities $N$(HI) $\approx 10^{22}$ cm$^{-2}$, i.e. 4–7 the value listed in Table 7 for NGC 660, and twice the value given for NGC 3628. However, the effective absorbing area is smaller by at least an order of magnitude than the large 21″ beam over which we have averaged our $H_2$ in Table 7.

importantly, in these highly tilted galaxies much of the HI seen in absorption must reside in the disk, and the actual HI content of the central region is unknown (see also the discussion by Baan et al. 1992). Although we have no direct knowledge of central HI column densities in the present sample, we note that most (if not all) galaxies with strong central molecular gas concentrations exhibit a pronounced lack of HI emission at their centers. In the six more or less face-on galaxies previously studied by us, we found a mean value $N$(HI) $= 0.6 \pm 0.3 \times 10^{21}$ cm$^{-2}$, and there is no reason to assume that the galaxies discussed here are very different.

Indeed, in the HI channel maps of NGC 4666, there is a clear lack of neutral hydrogen at the position of the nuclear CO peak (Walter et al. 2004, their Fig. 9). From the previous results, we estimate that the HI contribution to the total hydrogen column densities derived by us is small, typically 10 per cent uncertain by a factor two either way. However, the one face-on galaxy discussed here, NGC 278, clearly lacks a central molecular concentration and here the HI contribution may be significant.

The $H_2$ masses derived are again much lower than those calculated previously by authors who assumed the “standard” CO-to-$H_2$ conversion factor $X$ to apply. If we were to have underestimated the HI contribution, or to have overestimated the CO column density, these $H_2$ masses would be even lower. With the results presented for the galaxy centers in this paper, we find $X = 0.1–0.3 \times 10^{20}$ cm$^{-2}$/($K \times km \times s^{-1}$) which is a factor of 7–20 lower than the ‘standard’ Milky Way $X$ factors (see also Strong et al. 2004), but quite similar to those found in other galaxy centers (Israel 2009; Israel & Baas 2003, and references therein). We also note that at least for NGC 3628 our present result is practically identical to the low value ($X = 0.2–0.7 \times 10^{20}$ cm$^{-2}$/($K \times km \times s^{-1}$) found independently by Irwin & Sofue (1996). With the low $X$ values presented here, the molecular gas does not constitute more than typically a few per cent of the total (dynamical) mass in the same volume.

5.7. Temperature and excitation

Although a classical UV-illuminated photon-dominated region (PDR) associated with a star-forming region may reach quite high kinetic temperatures, the mass of gas at such elevated temperatures is rather small and limited to the immediate vicinity of the stellar heating source. Even in intense star-forming regions globally averaged temperatures are unlikely to be in excess of 20–30 K.

When we look at Table 6 we see that only towards the center of the fully edge-on galaxy NGC 3628 the molecular line emission may arise from a gas purely dominated by star-bursts. In the other four galaxy centers, a 10–30 K molecular gas component is always accompanied by a much hotter (usually relatively tenuous) component of temperature 100–150 K. In NGC 278 and NGC 660 this hot component contains, in effect, most of the molecular gas mass, in NGC 4666 it is about half, and only in the quiescent center of NGC 4631 it is a small (20%) fraction. Although the galaxies discussed here all have star-burst-dominated central regions, they are thus mostly too hot to be excited only by the UV photons from luminous stars. We found a similar result in the preceding paper on five AGN/star-burst galaxies (Israel 2009). There, as is the case here, central star-bursts were seen to produce extended outflows glowing in soft-X-ray emission. Also the galaxies included in this paper support the suggestion that the hot molecular gas component is efficiently heated by the X-rays from these flows (see Meijerink et al. 2006, 2007) rather than by the UV photons from the star-burst.
6. Conclusions

1. We have observed the centers of five galaxies undergoing significant star-burst activity in the first four transitions of 12CO and the first three transitions of 13CO, and three of them also in the lower transition of [CI].
2. All galaxies were mapped over at least 1′ × 1′ in the J = 2–1 and J = 3–2 transitions and over a smaller area in the J = 4–3 transition of 12CO.
3. The central line ratios, reduced to a standard 21′′ beam, vary significantly in the sample galaxies. In general, relatively strong J = 4–3 line emission indicates elevated densities and perhaps temperatures for the molecular gas.
4. 12CO optical depths appear not to be very high. NGC 660, NGC 3628, and NGC 4661 have 12CO/13CO ratios in the range of 11–16. NGC 278 and NGC 4631 have lower isotopic ratios in the range 6–8 suggesting the somewhat higher optical depths reminiscent of extended molecular clouds in the Solar Neighborhood.
5. In NGC 660, NGC 3628, and NGC 4666 molecular gas is present in the form of clearly identifiable central concentrations of outer radius R = 0.6–1.5 kpc. Such central concentrations are lacking in NGC 278 and NGC 4631. The central concentrations in NGC 660 and NGC 3628 exhibit a local minimum at the nucleus itself.
6. In the central regions of NGC 660, NGC 3628, and NGC 4666, we find moderate H2 masses of 0.6–1.5 × 10⁸ M☉. These masses are typically about one per cent of the dynamical mass in the same region. The CO-to-H2 conversion factors X implied by these masses and the observed J = 1–0 12CO line intensities is typically an order of magnitude lower than the “standard” Solar Neighborhood X-factor.
7. The molecular gas of all observed galaxies may at least partly be excited by UV-photons from the extended circumnuclear star-burst, but in all galaxies (except perhaps NGC 3628) a significant fraction of the molecular gas must be excited in other ways such as the X-rays seen to emanate from massive wind-driven outflows.

References

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5.8. Comparison with AGN central CO emission

A brief comparison with the galaxies containing a (modest) AGN, discussed in our previous paper (Israel 2009) shows a number of resemblances and differences. In galaxy centers of either type, we need to fit the observed CO lines with at least two different molecular gas density/temperature components: a hot and tenuous one, and a cooler and dense one. However, we find that the highest densities occur in galaxy centers that have both a star-burst and an AGN. The size of the central molecular gas concentration is similar whether or not an AGN is present, but its mass and column density are on average lower in the star-burst-only than in the combined star-burst/AGN galaxies. CO emission is also weaker in star-burst-only galaxies, which also tend to have lower 12CO/13CO ratios, hence higher average CO optical depths. The weakest CO galaxies in the sample (NGC 278 and NGC 4631) are pure star-burst galaxies without a significant central CO concentration. Rather, these galaxies confine their star-burst activity to the disk spiral arms. In galaxies of either type, the CO-to-H2 conversion factors X appropriate to the central region are low – there is no systematic difference. In terms of excitation, both galaxy center types require another mechanism to operate in addition to the UV excitation from PDRs. X-rays from diffuse gas heated by star-burst-driven winds may be the answer. In any case and at least on scales of a few hundred parsecs or more, (modest) AGNs do not seem to leave an unambiguous imprint on the centrally concentrated molecular gas.