

Molecular Gas Properties of the Giant Molecular Cloud Complexes in the Arms and Inter-arms of the Spiral Galaxy NGC 6946

Selçuk Topal^{1*}, Estelle Bayet¹, Martin Bureau¹, Timothy A. Davis², Wilfred Walsh³

¹*Sub-department of Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, U.K.*

²*European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748, Garching bei Muenchen, Germany*

³*Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, U.S.A.*

Accepted . Received ; in original form

ABSTRACT

Combining observations of multiple CO lines with radiative transfer modeling is a very powerful tool to investigate the physical properties of the molecular gas in galaxies. Using new observations as well as literature data, we provide the most complete CO ladders ever generated for eight star-forming regions in the spiral arms and inter-arms of the spiral galaxy NGC 6946, with observations of the CO(1-0), CO(2-1), CO(3-2), CO(4-3), CO(6-5), ¹³CO(1-0) and ¹³CO(2-1) transitions. For each region, we use the large velocity gradient assumption to derive beam-averaged molecular gas physical properties, namely the gas kinetic temperature (T_K), H₂ number volume density ($n(\text{H}_2)$) and CO number column density ($N(\text{CO})$). Two complementary approaches are used to compare the observations with the model predictions: χ^2 minimisation and likelihood. The physical conditions derived vary greatly from one region to the next: $T_K = 10\text{--}250$ K, $n(\text{H}_2) = 10^{2.3}\text{--}10^{7.0}$ cm⁻³ and $N(\text{CO}) = 10^{15.0}\text{--}10^{19.3}$ cm⁻². The spectral line energy distribution (SLED) of some of these extranuclear regions indicates a star-formation activity that is more intense than that at the centre of our own Milky Way. The molecular gas in regions with a large SLED turnover transition ($J_{\text{max}} > 4$) is hot but tenuous with a high CO column density, while that in regions with a low SLED turnover transition ($J_{\text{max}} \leq 4$) is cold but dense with a low CO column density. We finally discuss and find some correlations between the physical properties of the molecular gas in each region and the presence of young stellar population indicators (supernova remnants, H II regions, H I holes, etc).

Key words: galaxies: spiral – galaxies: star formation – galaxies: ISM – ISM: molecules – ISM: clouds.

1 INTRODUCTION

The interstellar medium (ISM) of galaxies has many phases, each one with its own temperature, density, chemical composition, etc. At high densities, molecular hydrogen (H₂) dominates and provides the reservoir for star formation (SF). Since its detection in the ISM by e.g. Wilson et al. (1970), Solomon et al. (1971) and Penzias et al. (1971), the ground-state rotational transition ($J=1\text{--}0$) of the CO molecule (second most abundant in the ISM) has become the most widely used tracer of H₂, with an excitation temperature of ≈ 5 K and a wavelength of 2.6 mm readily observable from the ground.

Stars form in the densest parts of giant molecular clouds (GMCs), spanning tens of parsecs and weighting $\sim 10^4\text{--}10^6 M_\odot$ (Kirk 2011). The exact conditions under which star forms are however still poorly understood, and must ultimately depend on the local physical conditions in the dense gas. In this paper, we thus aim to constrain the physical conditions in the star-forming regions of

one particular galaxy, NGC 6946, in the hope of futhering our understanding of SF processes.

NGC 6946 is an almost face-on, nearby (5.5 Mpc; Tully 1988) spiral galaxy whose basic properties are listed in Table 1. It has been intensively studied at all wavelengths, making it a particularly good target to study SF processes using a multitude of tracers. Figure 1 shows H α and H I images of NGC 6946, along with the location of a number of features discussed below. In addition, the 8 key regions on which our analysis will focus are identified there.

The star formation rate (SFR) of NGC 6946 is higher than that of the Milky Way (DeGioia-Eastwood et al. 1984; Sauty et al. 1998; Karachentsev et al. 2005). Extensive CO(1-0) (Tacconi & Young 1989; Walsh et al. 2002), CO(2-1) (Leroy et al. 2009) and CO(3-2) (Walsh et al. 2002) observations of NGC 6946 are available in the literature, and we will present here new data comprising one of the most extensive CO(2-1) maps. More limited mapping of the molecules HCN, HCO and CO also exist in the central regions (Ball et al. 1985; Weliachew et al. 1988; Bonnarel et al. 1988; Ishizuki et al. 1990; Regan & Vogel 1995; Nieten et al. 1999; Levine et al.

* E-mail: selcuk.topal@astro.ox.ac.uk.

Table 1. General properties of NGC 6946

Property	Value	Reference
Type	SABcd	1
RA (J2000)	20 ^h 34 ^m 52. ^s 3	2
Dec (J2000)	60° 09' 13''	2
Distance	5.5 Mpc	3
Major-axis diameter	11'5	1
Minor-axis diameter	9'8	1
Position angle	243°	4
Inclination	33°	4
M_{H_2}	$1.2 \pm 0.1 \times 10^{10} M_{\odot}$	5
V_{\odot}	40 km s ⁻¹	6
SFR	3.12 M_{\odot} yr ⁻¹	7

References: (1) NASA/IPAC Extragalactic Database (NED); (2) Skrutskie et al. (2006); (3) Tully (1988); (4) de Blok et al. (2008); (5) Tacconi & Young (1989); (6) Epinat et al. (2008); (7) Karachentsev et al. (2005).

2008), and the molecular gas physical properties have been studied in the centre (Walsh et al. 2002; Bayet et al. 2006) and one position in the arms (Walsh et al. 2002). Here, we will extend this analysis to all 8 regions defined in Figure 1.

As shown in Figure 1, NGC 6946 has prominent East/North-East spiral arms and more flocculent West/South-West arms (Arp 1966), allowing us to probe possible differences in the gas physical properties as a function of radius in two physically different parts of the galaxy. Interestingly, NGC 6946 has hosted 9 recorded supernovae in the last 100 years (3 in the past 10 years alone), the highest number in any galaxy (Schlegel 1994; Fridriksson et al. 2008). The rate of supernova explosions at the centre of NGC 6946 is as high as $6 \times 10^{-3} \text{ yr}^{-1}$ (Engelbracht et al. 1996). Radio-bright (35; Lacey & Duric 2001) and optically-selected (27; Matonick & Fesen 1997) supernova remnants (SNRs) have also been detected. Some of the regions probed in our study are associated with some of these SNRs (see Fig. 1). This SNR richness implies the presence of a young stellar population, and it suggests an environment very rich in cosmic rays (CRs) produced during supernova explosions. This in turn allows us to probe for the first time in this source the possible relationship between supernovae and molecular gas physical conditions.

A catalogue of 643 HII regions was published by Bonnarel et al. (1986), who found that the HII regions on the eastern side of NGC 6946 are ≈ 30 per cent larger than those on western side. Many of these HII regions are associated with regions studied here, including two giant HII complexes (Fig. 1). Ten star-forming regions were studied in details by Murphy et al. (2010), who detected 33 GHz free-free emission and showed that it is as useful a tool to derive SFRs as any other standard diagnostic.

Over 100 HI holes have also been found in NGC 6946, most located in the inner regions where the gas density and SFR are high (Boomsma et al. 2008). HI holes are thought to be created by supernovae and stellar winds (Tomisaka & Ikeuchi 1986; McCray & Kafatos 1987; Mac Low & McCray 1988; Tenorio-Tagle & Bodenheimer 1988), and some of the regions we study directly coincide with holes, while others are located in their vicinity (see Fig. 1).

As for the fuel for star formation, Donovan Meyer et al. (2012) found more than 100 GMCs within the central 5 kpc of NGC 6946, with sizes ranging from 40 to 200 pc. Similarly, Rebolledo et al. (2012) studied a $6 \times 6 \text{ kpc}^2$ area in the eastern part of NGC 6946 (where regions 1, 2 and 7 of this work are located) and found 45 CO complexes and 64 GMCs (see Fig. 1).

As the physical conditions and thus the SF processes of external galaxies may differ dramatically from those in the Milky Way,

we specifically aim here to probe these SF processes in the presence of SNRs, stellar winds, HI holes, etc. All have the potential to significantly perturb both the dynamics and the thermal balance of GMCs. In this paper, we therefore study in details 8 carefully-selected regions in the spiral arms and inter-arms of NGC 6946 (see Fig. 1). We probe the molecular gas physical properties in these regions through the large velocity gradient (LVG) method (Goldreich & Kwan 1974; de Jong et al. 1975), using the non-local thermodynamic equilibrium (non-LTE) radiative transfer code RADEX (van der Tak et al. 2007), and exploiting the flux ratios of multiple CO transitions. Our specific goals are first to probe the gas physical conditions in various key regions of the galaxy, second to compare the conditions in the various regions (galaxy centre, spiral arms and inter-arms), and last to identify the main drivers of the gas physical conditions.

This paper is set up as follows. Section 2 describes our own CO observations, the literature data we exploit, and their common data reduction. Section 3 presents the radiative transfer code adopted to model the molecular gas properties, and the two complementary methods used to identify the best models. In Section 4, we present the outcome of our own observations and the physical parameters of the best-fit models. A discussion of the derived parameters in relation to the characteristics and environment of each region is presented in Section 5. We conclude briefly in Section 6.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

Caltech Submillimeter Observatory (CSO) 10.4-m telescope observations of the CO(2-1), CO(3-2), CO(4-3), CO(6-5) and $\text{CI}({}^3\text{P}_1 - {}^3\text{P}_0)$ lines were performed in 2003-2005 in atmospheric conditions varying from good to excellent ($\tau_{225 \text{ GHz}} \lesssim 0.1$). The spatial coverage of the observations in each line is shown in Figure 2, overlaid on an optical image (Digitized Sky Survey, DSS). The CO(2-1) observations cover a $510'' \times 510''$ contiguous region centred on the galaxy, with a full-width at half-maximum (FWHM) beam size of $31''.5$. The CO(3-2) observations consist of clusters of pointings around the galaxy centre, region 1 and region 2, and a series of pointings along the major-axis toward the East (beam size $21''$). The CO(4-3) observations consist of a cluster of pointings around the galaxy centre, and a single pointing around region 1 and region 2 (beam size $15''.7$). The same applies to CO(6-5), although region 2 was not observed (beam size $10''.5$). The $\text{CI}({}^3\text{P}_1 - {}^3\text{P}_0)$ observations have only a few pointings along the major-axis toward the East (beam size $14''.7$).

The main observational parameters of the CSO observations are listed in Table 2. All observations used the superconducting tunnel junction receivers operated in double side-band mode. We adopted a $3'$ chopping throw for the CO(2-1), CO(3-2), CO(4-3) and $\text{CI}({}^3\text{P}_1 - {}^3\text{P}_0)$ lines, but a throw of only $1'$ for the CO(6-5) transition as its emission is more compact. The spectra were obtained with two acousto-optic spectrometers with effective bandwidths of 1000 and 500 MHz and spectral resolutions of ≈ 1.5 and 2 MHz, respectively. There was no sign of contamination by emission in the off beams in any spectrum. The pointing was checked using planets (Jupiter, Mars and Saturn) and evolved stars (IRC 10216 and R Hya), yielding a pointing accuracy of $\approx 5''$. The overall flux calibration is good to ≈ 20 per cent.

We list our CSO detections (with a peak signal-to-noise ratio $S/N \geq 3$) in Table A1 of Appendix A and show the spectra

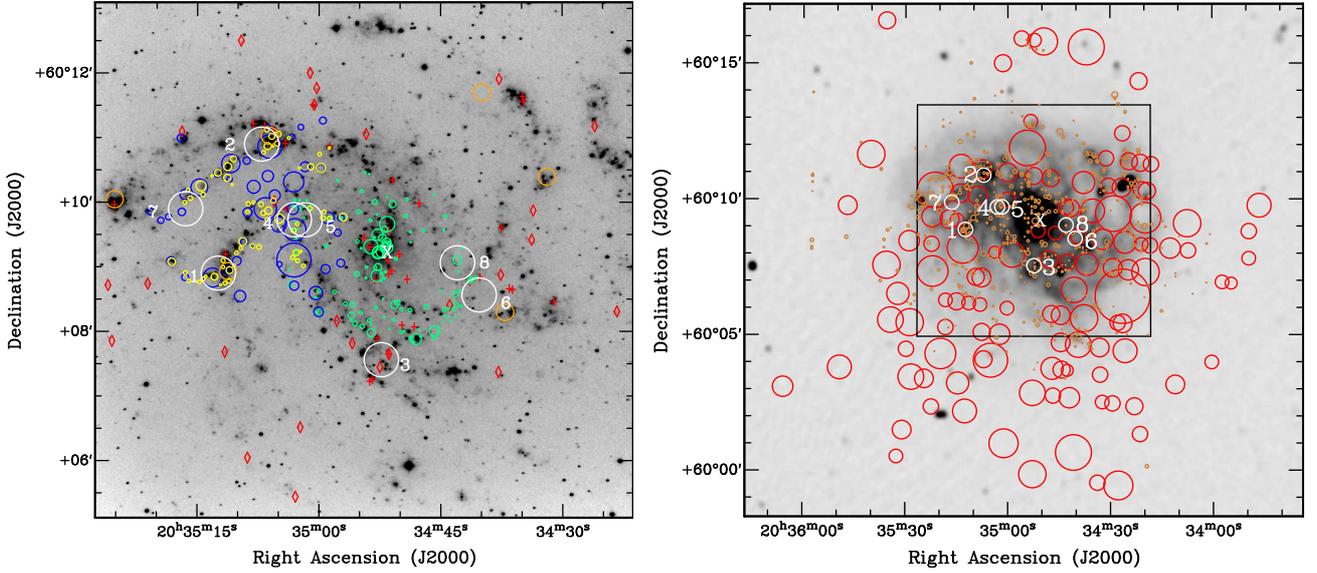


Figure 1. Regions studied and star formation-related features in NGC 6946. Left: $H\alpha$ image of NGC 6946 (Knapen 2004). Overlaid green, yellow, blue and orange circles indicate respectively GMCs in the central 5 kpc (Donovan Meyer et al. 2012), GMCs in the eastern part (Rebolledo et. al 2012), CO(1-0) complexes in the eastern part (Rebolledo et. al 2012), and giant HII complexes (van der Kruit et al. 1977). Red crosses and diamonds indicate supernova remnants identified in the radio (Lacey & Duric 2001) and optical (Matonick & Fesen 1997), respectively. Right: HI map of NGC 6946 (Braun et al. 2007). Overlaid red circles and brown dots represent HI holes (Boomsma 2007) and HII regions (Bonnarel et al. 1986), respectively. White circles with numbers in both images represent the 8 regions studied in this paper, with our final common beam size of $31'' \times 5''$, while the white “X” identifies the centre of the galaxy. The black square on the larger HI map shows our CO(2-1) pointings, covering a contiguous area of $510'' \times 510''$ centred on the galaxy. North is up and East to the left in all images.

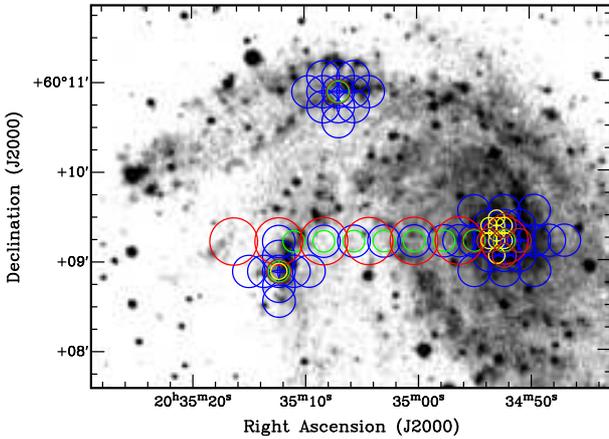


Figure 2. NGC 6946 optical image (DSS), overlaid with the grid of CSO pointings for the CO(3-2) (blue), CO(4-3) (brown), CO(6-5) (yellow) and CI(3P_1 - 3P_0) (green) lines. The circles have a diameter equal to the beam size (FWHM) of each line. The CO(2-1) pointings cover a much larger contiguous area of $510'' \times 510''$ centred on the galaxy (see Fig. 1), so only a few representative pointings are shown in red along the major-axis.

in Figure B1 of Appendix B. The CO(2-1) integrated intensity and mean velocity maps are presented in Figure 3, overlaid on an optical image (DSS). These are some of the largest CO(2-1) maps of NGC 6946 ever presented, with an average RMS noise level of $T_{\text{mb}} = 45$ mK. Finally, we also show in Figure 4 the radial distribution of the various molecular lines observed. As we do not have full spa-

Table 2. CSO observational parameters.

Line	Rest frequency (GHz)	Beam size (arcsec)	Linear distance (kpc)	$\eta_{\text{mb}}^{\text{a}}$
CO(2-1)	230.538	31.5	0.84	0.70
CO(3-2)	345.795	21.0	0.56	0.75
CO(4-3)	461.040	15.7	0.42	0.50
CO(6-5)	691.473	10.5	0.28	0.50
CI(3P_1 - 3P_0)	492.160	14.7	0.39	0.53

^a Main beam efficiency (<http://www.submm.caltech.edu/cso/>).

tial coverage for all lines (see above), standard azimuthal averages on ellipses are not possible, and we simply took linear cuts along the major-axis toward the East. We however also note a detection of CO(6-5) at a distance of ≈ 4 kpc from the centre toward the East (region 1; see Table 3).

2.2 Literature data

In addition to our own CSO observations described above (CO(2-1), CO(3-2), CO(4-3) and CO(6-5)), we use complementary data from Walsh et al. (2002): CO(1-0) in region 1; CO(1-0), $^{13}\text{CO}(1-0)$ and $^{13}\text{CO}(2-1)$ in region 2; CO(1-0), CO(3-2) and $^{13}\text{CO}(2-1)$ in regions 3, 4, 5, 6 and 8; and CO(1-0), CO(3-2) and CO(4-3) in region 7. The CO(1-0) and $^{13}\text{CO}(1-0)$ observations were obtained at the Institut de Radioastronomie Millimetrique (IRAM) 30-m telescope with beam sizes of $21'' \times 8''$ and $22'' \times 8''$, respectively. The CO(3-2), CO(4-3) and $^{13}\text{CO}(2-1)$ observations were obtained at the Heinrich Hertz 10-m Telescope (HHT) with beam sizes of $21'' \times 8''$, $16'' \times 4''$ and $34'' \times 3''$, respectively. We refer the reader to Walsh et al. (2002) for further information on these observations.

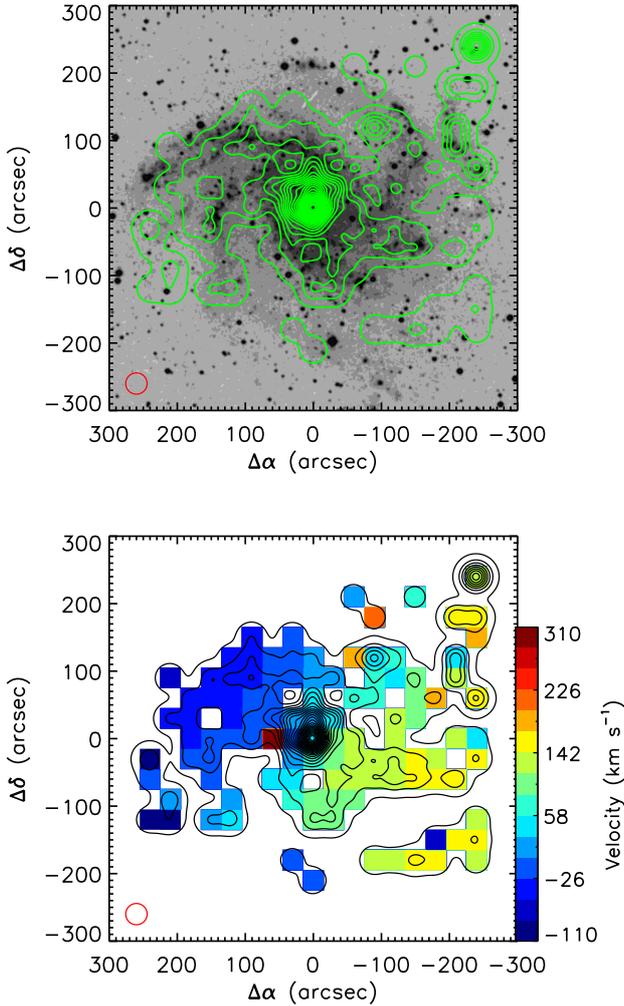


Figure 3. Top: NGC 6946 CO(2-1) integrated line intensity map (green contours), overlaid on an optical image (DSS). Bottom: Same CO(2-1) integrated line intensity map (black contours), overlaid on the CO(2-1) mean velocity field. Contours are from 1 to 80 per cent of the peak integrated intensity of 100 K km s^{-1} , in steps of 5 per cent. The CO(2-1) beam of $31''.5$ is shown in red in the bottom-left corner of each panel.

2.3 Data reduction

Both our own CSO data and the literature data from the IRAM 30-m telescope and HHT were consistently (re-)reduced using the Continuum and Line Analysis Single-Dish Software (CLASS) software package in the Grenoble Image and Line Analysis System (GILDAS). A baseline fit (polynomial of order 0 or 1, occasionally 2) was removed from each scan before averaging all integrations. Then, for each line in each region, a Gaussian was fit to the integrated spectrum to derive the velocity-integrated line intensity S (in K km s^{-1}). The fits are shown in Figure B1 of Appendix B, overlaid on the spectra. The integrated line intensity was then transformed from the antenna temperature scale (T_A^*) to the main beam brightness temperature scale (T_{mb}) by dividing by the main beam efficiency (η_{mb}). The main beam efficiencies for the IRAM 30-m telescope and HHT observations were taken from Walsh et al. (2002). The velocity-integrated line intensities and velocity widths (full width at half maximum, FWHM) are listed in Table A1.

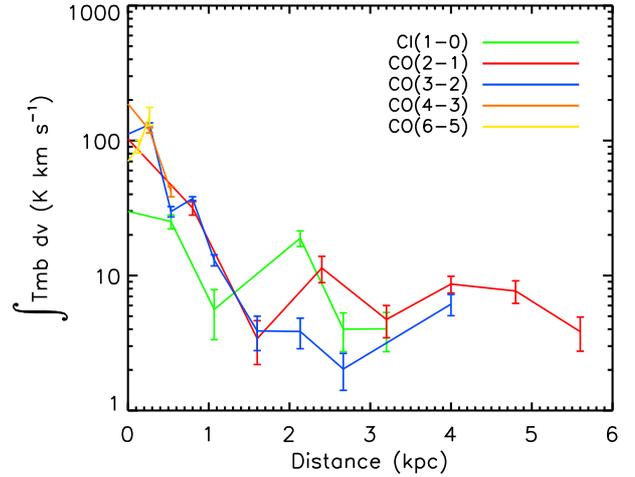


Figure 4. Radial distribution of the molecular gas in NGC 6946. The surface density profiles were obtained by taking a straight linear cut along the major-axis toward the East for each line. All surface density profiles decrease rapidly within $\approx 1 \text{ kpc}$ and then remain nearly flat. Colours are as in Figure 2.

To estimate the beam-averaged total intensities per unit area I and fluxes F , we used the standard expressions below (see also Bayet et al. 2004):

$$\frac{I}{\text{W m}^{-2} \text{sr}^{-1}} = 1.02 \times 10^{-18} \left(\frac{\nu}{\text{GHz}} \right)^3 \left(\frac{S}{\text{K km s}^{-1}} \right), \quad (1)$$

$$\frac{F}{\text{W m}^{-2}} = \left(\frac{I}{\text{W m}^{-2} \text{sr}^{-1}} \right) \left(\frac{\Omega_{\text{B}}}{\text{sr}} \right), \quad (2)$$

$$\frac{\Omega_{\text{B}}}{\text{sr}} = 1.133 \left(\frac{\theta_{\text{B}}^2}{\text{arcsec}^2} \right) \left(\frac{1}{206265^2} \right), \quad (3)$$

$$\frac{\theta_{\text{B}}}{\text{rad}} = 1.22 \frac{\lambda}{D}, \quad (4)$$

where ν and λ are respectively the observed line frequency and wavelength, Ω_{B} is the solid angle sustained by the beam, θ_{B} is the beam size (FWHM) and D is the diameter of the telescope.

After calculating the integrated line intensity for each region and line on which our analysis focuses, using both our and literature data, we applied beam dilution corrections to all measured quantities to express them for a single, common spatial resolution, chosen here to be the CO(2-1) beam size of $31''.5$. Under the assumption that all the emission in each region comes from the same cloud, we have corrected our values for beam dilution assuming a fixed source size for each region. Similarly to Walsh et al. (2002) and Bayet et al. (2006), we used the highest spatial resolution map available for the size measurements. As no molecular gas map exists at sufficiently high resolution, we used instead the $24 \mu\text{m}$ image from the Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003).

Specifically, to calculate each source size, we first considered a circular zone equal to the adopted beam (diameter $31''.5$) centred on each region. We then calculated the total area with a flux above 50 per cent of the peak within this zone, and took the source size as the diameter of a circle with that same area. We thus measured source sizes of 7.8, 9.3, 22.1, 15.6, 5.9, 19.9, 9.7 and $19''.5$ for

Table 3. Beam-corrected line quantities.

Region	Position ($\Delta\alpha''$, $\Delta\delta''$)	Radius ^a (kpc)	Line	k	$\int T_{\text{mb}} \text{d}v^{\text{b}}$ (K km s ⁻¹)	Intensity (W m ⁻² sr ⁻¹)	Flux (W m ⁻²)	FWHM (km s ⁻¹)
1	(150, -20)	4.04	CO(1-0)	0.51	8.73 ± 0.37	1.36 ± 0.06 × 10 ⁻¹¹	3.60 ± 0.15 × 10 ⁻¹⁹	24.9 ± 1.1
			CO(2-1)	1.00	9.16 ± 1.40	1.14 ± 0.18 × 10 ⁻¹⁰	3.02 ± 0.46 × 10 ⁻¹⁸	27.5 ± 4.6
			CO(3-2)	0.48	5.12 ± 0.70	2.16 ± 0.29 × 10 ⁻¹⁰	5.71 ± 0.78 × 10 ⁻¹⁸	26.8 ± 4.3
			CO(4-3)	0.29	3.90 ± 0.55	3.89 ± 0.55 × 10 ⁻¹⁰	1.03 ± 0.14 × 10 ⁻¹⁷	27.5 ± 5.1
			CO(6-5)	0.16	2.27 ± 0.78	7.63 ± 2.63 × 10 ⁻¹⁰	2.01 ± 0.70 × 10 ⁻¹⁷	20.2 ± 8.3
2	(110, 100)	3.96	CO(1-0)	0.52	8.25 ± 0.42	1.29 ± 0.07 × 10 ⁻¹¹	3.41 ± 0.18 × 10 ⁻¹⁹	28.7 ± 1.7
			CO(2-1)	1.00	8.74 ± 1.48	1.09 ± 0.19 × 10 ⁻¹⁰	2.89 ± 0.48 × 10 ⁻¹⁸	44.6 ± 8.2
			CO(3-2)	0.49	5.49 ± 0.36	2.31 ± 0.15 × 10 ⁻¹⁰	6.12 ± 0.40 × 10 ⁻¹⁸	34.1 ± 2.4
			CO(4-3)	0.31	2.89 ± 0.39	2.89 ± 0.39 × 10 ⁻¹⁰	7.64 ± 1.02 × 10 ⁻¹⁸	27.1 ± 3.9
			¹³ CO(1-0)	0.56	1.05 ± 0.10	1.42 ± 0.13 × 10 ⁻¹²	3.77 ± 0.35 × 10 ⁻²⁰	29.3 ± 3.1
¹³ CO(2-1)	0.20	0.45 ± 0.06	4.96 ± 0.63 × 10 ⁻¹²	1.31 ± 0.17 × 10 ⁻¹⁹	28.1 ± 4.0			
3	(0, -100)	2.67	CO(1-0)	0.63	7.54 ± 0.45	1.18 ± 0.07 × 10 ⁻¹¹	3.11 ± 0.19 × 10 ⁻¹⁹	26.2 ± 1.9
			CO(2-1)	1.00	7.80 ± 1.78	9.74 ± 2.22 × 10 ⁻¹¹	2.57 ± 0.59 × 10 ⁻¹⁸	36.2 ± 11.3
			CO(3-2)	0.63	6.76 ± 1.12	2.85 ± 0.47 × 10 ⁻¹⁰	7.53 ± 1.24 × 10 ⁻¹⁸	32.4 ± 6.9
			¹³ CO(2-1)	1.13	1.43 ± 0.26	1.56 ± 0.28 × 10 ⁻¹¹	4.12 ± 0.75 × 10 ⁻¹⁹	30.6 ± 7.5
4	(80, 30)	2.28	CO(1-0)	0.58	4.75 ± 0.45	7.42 ± 0.70 × 10 ⁻¹²	1.96 ± 0.18 × 10 ⁻¹⁹	15.9 ± 1.7
			CO(2-1)	1.00	11.14 ± 1.76	1.39 ± 0.22 × 10 ⁻¹⁰	3.68 ± 0.58 × 10 ⁻¹⁸	39.4 ± 8.3
			CO(3-2)	0.58	2.53 ± 0.53	1.07 ± 0.23 × 10 ⁻¹⁰	2.82 ± 0.59 × 10 ⁻¹⁸	13.2 ± 3.6
			¹³ CO(2-1)	1.15	1.61 ± 0.39	1.75 ± 0.43 × 10 ⁻¹¹	4.63 ± 1.12 × 10 ⁻¹⁹	17.3 ± 5.2
5	(70, 30)	2.03	CO(1-0)	0.65	5.73 ± 0.34	8.95 ± 0.53 × 10 ⁻¹²	2.36 ± 0.14 × 10 ⁻¹⁹	15.6 ± 1.1
			CO(2-1)	1.00	13.07 ± 1.98	1.63 ± 0.25 × 10 ⁻¹⁰	4.32 ± 0.65 × 10 ⁻¹⁸	53.5 ± 10.1
			CO(3-2)	0.65	3.90 ± 0.49	1.65 ± 0.21 × 10 ⁻¹⁰	4.35 ± 0.55 × 10 ⁻¹⁸	19.2 ± 3.0
			¹³ CO(2-1)	1.12	0.72 ± 0.12	7.89 ± 1.35 × 10 ⁻¹²	2.08 ± 0.36 × 10 ⁻¹⁹	20.9 ± 3.9
6	(-90, -40)	2.63	CO(1-0)	0.49	4.77 ± 0.43	7.46 ± 0.67 × 10 ⁻¹²	1.97 ± 0.18 × 10 ⁻¹⁹	24.1 ± 2.5
			CO(2-1)	1.00	7.95 ± 1.66	9.93 ± 2.08 × 10 ⁻¹¹	2.63 ± 0.55 × 10 ⁻¹⁸	27.6 ± 7.3
			CO(3-2)	0.49	3.21 ± 0.51	1.35 ± 0.21 × 10 ⁻¹⁰	3.58 ± 0.56 × 10 ⁻¹⁸	37.9 ± 5.6
			¹³ CO(2-1)	1.18	1.24 ± 0.20	1.35 ± 0.22 × 10 ⁻¹¹	3.58 ± 0.58 × 10 ⁻¹⁹	25.4 ± 4.3
7	(180, 40)	4.92	CO(1-0)	0.52	3.67 ± 0.43	5.73 ± 0.66 × 10 ⁻¹²	1.51 ± 0.17 × 10 ⁻¹⁹	22.3 ± 2.9
			CO(2-1)	1.00	8.42 ± 1.84	1.05 ± 0.23 × 10 ⁻¹⁰	2.78 ± 0.61 × 10 ⁻¹⁸	34.9 ± 9.9
			CO(3-2)	0.52	2.36 ± 0.61	9.95 ± 2.59 × 10 ⁻¹¹	2.63 ± 0.68 × 10 ⁻¹⁸	17.7 ± 4.3
			CO(4-3)	0.33	1.07 ± 0.22	1.07 ± 0.22 × 10 ⁻¹⁰	2.83 ± 0.59 × 10 ⁻¹⁸	16.7 ± 4.9
8	(-70, -10)	1.89	CO(1-0)	0.62	7.32 ± 0.44	1.14 ± 0.07 × 10 ⁻¹¹	3.02 ± 0.18 × 10 ⁻¹⁹	27.8 ± 1.9
			CO(2-1)	1.00	6.45 ± 1.22	8.06 ± 1.52 × 10 ⁻¹¹	2.13 ± 0.40 × 10 ⁻¹⁸	22.6 ± 4.0
			CO(3-2)	0.62	3.87 ± 0.58	1.63 ± 0.25 × 10 ⁻¹⁰	4.31 ± 0.65 × 10 ⁻¹⁸	24.4 ± 4.5
			¹³ CO(2-1)	1.07	0.51 ± 0.12	5.54 ± 1.25 × 10 ⁻¹²	1.46 ± 0.33 × 10 ⁻¹⁹	18.7 ± 4.9

^aRadii are calculated with respect to the galaxy centre. ^bThe CO(2-1) integrated intensities and the line widths were obtained by interpolating the two closest detections of the large-scale mapping.

regions 1 to 8, respectively. Although the area with a flux above 50 per cent of the peak is not contiguous in regions 3, 4 and 8, the secondary peaks are much smaller in both area and flux and should therefore have little impact on our modelling results. In any case, although this method of measuring source sizes is only approximate, all the lines in a given region are corrected to the same source size, so the method adopted only has a small effect on the final line ratios used in the modeling (see Section 3). Indeed, reducing the source sizes by 50 per cent (thus the source areas by a factor of 4) or increasing the source sizes by 50 per cent (thus the source areas by a factor of ≈ 2) only changes the line ratios by ≈ 12 per cent on average.

A beam dilution correction factor k was calculated for each line and each region using the source factor calculated and a method similar to that described in Walsh et al. (2002) and Bayet et al.

(2006):

$$k = (\theta_{\text{line}}^2 + \theta_{\text{source}}^2) / (\theta_{\text{common}}^2 + \theta_{\text{source}}^2), \quad (5)$$

where θ_{line} is the beam size of the observations for the line considered, θ_{common} is the common beam size adopted (here 31''5) and θ_{source} is the source size of the region considered. The correction factors obtained for all lines and all regions are listed in Table 3.

Following this, the beam dilution-corrected integrated line intensities (K km s⁻¹), beam-averaged total intensities (W m⁻² sr⁻¹) and total fluxes (W m⁻²) for the 8 regions studied were calculated and are also listed in Table 3. These are the values we will refer to and use in the rest of this paper, in particular for the line ratio analysis discussed in Section 3. The line ratios computed using these beam dilution-corrected values are listed in Table 4.

Table 4. Beam-corrected line ratios.

Region	Line Ratio	Value
1	$^{12}\text{CO}(2-1) / ^{12}\text{CO}(1-0)$	1.05 ± 0.17
	$^{12}\text{CO}(3-2) / ^{12}\text{CO}(1-0)$	0.59 ± 0.08
	$^{12}\text{CO}(4-3) / ^{12}\text{CO}(1-0)$	0.45 ± 0.07
	$^{12}\text{CO}(6-5) / ^{12}\text{CO}(1-0)$	0.26 ± 0.09
2	$^{12}\text{CO}(2-1) / ^{12}\text{CO}(1-0)$	1.06 ± 0.19
	$^{12}\text{CO}(3-2) / ^{12}\text{CO}(1-0)$	0.66 ± 0.06
	$^{12}\text{CO}(4-3) / ^{12}\text{CO}(1-0)$	0.35 ± 0.05
	$^{13}\text{CO}(1-0) / ^{12}\text{CO}(1-0)$	0.13 ± 0.01
	$^{13}\text{CO}(2-1) / ^{12}\text{CO}(2-1)$	0.05 ± 0.01
3	$^{12}\text{CO}(2-1) / ^{12}\text{CO}(1-0)$	1.03 ± 0.24
	$^{12}\text{CO}(3-2) / ^{12}\text{CO}(1-0)$	0.90 ± 0.16
	$^{13}\text{CO}(2-1) / ^{12}\text{CO}(2-1)$	0.18 ± 0.05
4	$^{12}\text{CO}(2-1) / ^{12}\text{CO}(1-0)$	2.34 ± 0.43
	$^{12}\text{CO}(3-2) / ^{12}\text{CO}(1-0)$	0.53 ± 0.12
	$^{13}\text{CO}(2-1) / ^{12}\text{CO}(2-1)$	0.14 ± 0.04
5	$^{12}\text{CO}(2-1) / ^{12}\text{CO}(1-0)$	2.28 ± 0.37
	$^{12}\text{CO}(3-2) / ^{12}\text{CO}(1-0)$	0.68 ± 0.09
	$^{13}\text{CO}(2-1) / ^{12}\text{CO}(2-1)$	0.06 ± 0.01
6	$^{12}\text{CO}(2-1) / ^{12}\text{CO}(1-0)$	1.67 ± 0.38
	$^{12}\text{CO}(3-2) / ^{12}\text{CO}(1-0)$	0.67 ± 0.12
	$^{13}\text{CO}(2-1) / ^{12}\text{CO}(2-1)$	0.16 ± 0.04
7	$^{12}\text{CO}(2-1) / ^{12}\text{CO}(1-0)$	2.30 ± 0.57
	$^{12}\text{CO}(3-2) / ^{12}\text{CO}(1-0)$	0.64 ± 0.18
	$^{12}\text{CO}(4-3) / ^{12}\text{CO}(1-0)$	0.29 ± 0.07
8	$^{12}\text{CO}(2-1) / ^{12}\text{CO}(1-0)$	0.88 ± 0.17
	$^{12}\text{CO}(3-2) / ^{12}\text{CO}(1-0)$	0.53 ± 0.09
	$^{13}\text{CO}(2-1) / ^{12}\text{CO}(2-1)$	0.08 ± 0.02

3 MODELING

3.1 Radiative transfer code

The radiative transfer equations need to be solved to probe the physical conditions of the molecular gas. This is achieved here applying RADEX (van der Tak et al. 2007), a non-LTE radiative transfer code using the LVG approximation (Goldreich & Kwan 1974; de Jong et al. 1975) and yielding line intensities as a function of a set of user-specified parameters: gas kinetic temperature T_K , molecular hydrogen number volume density $n(\text{H}_2)$ and CO number column density per unit line width $N(\text{CO})/\Delta v$. Here we take the FWHM of the Gaussian fit of each line as the line width Δv (see Table 3).

The LVG approximation assumes a one-dimensional (1D) isothermal ISM with a velocity gradient sufficiently large to ensure that the source function is locally defined. RADEX computes the first level populations using statistical equilibrium in the optically thin limit and considering a background radiation field (taken here to be a black body with temperature 2.73 K), and then calculates the optical depths of the lines. RADEX further calculates both the internally-generated radiation and the integrated intensity of the lines as background-subtracted Rayleigh-Jeans equivalent radiation temperatures. We assume here a uniform spherical geometry.

In our models, the range of parameters considered is: $T_K = 10$ to 250 K in steps of 5 K, $n(\text{H}_2) = 10^2$ to 10^7 cm^{-3} in

steps of $10^{0.25} \text{ cm}^{-3}$ and $N(\text{CO}) = 10^{15}$ to 10^{21} cm^{-2} in steps of $10^{0.25} \text{ cm}^{-2}$. The collisional rate coefficients between the molecules H_2 , CO and ^{13}CO have been measured by several authors (e.g. Green & Thaddeus 1976; Schinke et al. 1985; Flower & Launay 1985) and we use here the Leiden Atomic and Molecular Database (LAMDA; Schoier et al. 2005; Yang et al. 2010) for the most recent data. The ortho- to para- H_2 ratio is assumed to be thermalised at the given kinetic temperature. The CO/ ^{13}CO isotopic abundance ratio is taken to be 40 (Henkel & Mauersberger 1993; Israel & Bass 2001; Bayet et al. 2006) for the regions where ^{13}CO observations are available.

3.2 Best-fit models

We use a standard χ^2 approach to identify the best-fit model in each region. For each region and each set of model parameters (T_K , $n(\text{H}_2)$, $N(\text{CO})$), the χ^2 is defined as

$$\chi^2 \equiv \sum_i \left(\frac{R_{i,\text{mod}} - R_{i,\text{obs}}}{\Delta R_{i,\text{obs}}} \right)^2, \quad (6)$$

where R_{mod} is the modeled line ratio, R_{obs} is the observed line ratio with uncertainty ΔR_{obs} (see Table 4), and the summation is over all independent line ratios i for that region (one fewer than the number of lines available for that region). The best-fit model parameters for each region are listed in Table 5 and are taken as the set of parameters yielding the smallest χ^2 (χ_{min}^2).

We also plot in Figure 5 the contours of $\Delta\chi^2 \equiv \chi^2 - \chi_{\text{min}}^2$ in (T_K , $n(\text{H}_2)$, $N(\text{CO})$) space, to illustrate the uncertainties of the best-fit models and the usual degeneracies between the model parameters. The only way to break those degeneracies is to add observations of other lines coming from the same (or similar) gas phase as the current CO lines, e.g. low- J HCN lines (with similar critical densities; see e.g. Jansen 1995).

3.3 Likely models

Following Bayet et al. (2013), we additionally applied the likelihood method to our models, calculating for each region the probability distribution function (PDF) of each model parameter. That is, for each possible value of a model parameter, we calculated the sum of the $e^{-\Delta\chi^2/2}$ for all possible values of the other two parameters. These PDFs are shown in Figure 6 along with their peak (most likely) and median values within the model grid, as well as the 68 per cent (1σ) confidence levels around the median (following Kaviraj et al. 2007). The latter values are listed in Table 5.

4 RESULTS

4.1 Empirical results

Figure 3 shows our new CO(2-1) integrated intensity and mean velocity maps of NGC 6946, some of the most extensive in the literature. Molecular gas traced by CO(2-1) emission is pervasive in NGC 6946, albeit concentrated along the spiral arms, and the velocity field is regular. Although our coverage is patchy, CO(3-2) emission (tracing slightly more excited gas) is particularly strong around regions 1 and 2, located in the prominent East/North-East spiral arms. These two regions are also very bright at H α (Knapen 2004), 24 μm (Kennicutt et al. 2003), 850 μm (Bianchi et al. 2000) and 6.2 cm (Beck & Hoernes 1996), suggesting intense SF in a

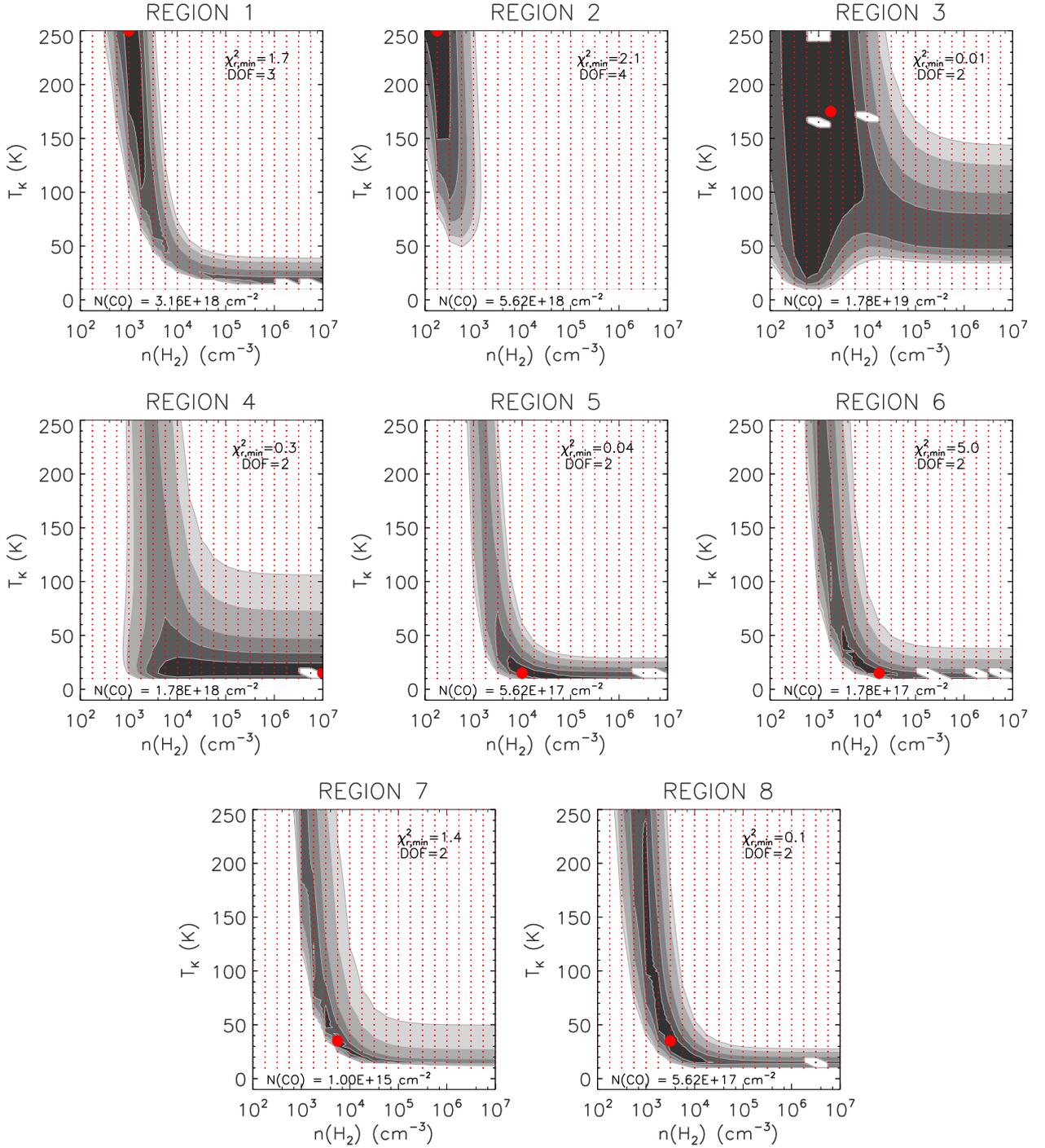


Figure 5. $\Delta\chi^2$ maps (contours and greyscales; see Section 3.2). For each region, $\Delta\chi^2$ is shown as a function of T_K and $n(\text{H}_2)$ for the best-fit $N(\text{CO})$ (indicated in the bottom-left corner of each panel). The model grid is indicated with red dots and the best-fit model with a red filled circle. Black dots represent bad models (e.g. unacceptably low opacity; see van der Tak et al. 2007). $\Delta\chi^2$ contours indicate the 1σ (darkest zone) to 5σ (lightest zone) confidence levels in steps of 1σ . For 3 line ratios (all regions except regions 1 and 2, 2 degrees of freedom), the levels are 2.3, 6.2, 11.8, 19.3 and 24.0. For 4 line ratios (region 1, 3 degrees of freedom), the levels are 3.5, 8.0, 14.2, 22.1 and 28.0. For 5 line ratios (region 2, 4 degrees of freedom), the levels are 4.7, 9.7, 16.3, 24.5 and 32.0. The reduced χ^2_{min} ($\chi^2_{\text{r,min}}$) values together with their corresponding degrees of freedom are also shown in each panel.

Table 5. Model results for the two best-model identification methods.

Region	Parameter	χ^2 minimisation	Likelihood	Region	Parameter	χ^2 minimisation	Likelihood		
1	T_K	250* K	153^{+69}_{-138} K	2	T_K	250* K	211^{+27}_{-42} K		
	$\log(n(\text{H}_2))$	3.0 cm^{-3}	$3.0^{+2.4}_{-0.6} \text{ cm}^{-3}$		$\log(n(\text{H}_2))$	2.3 cm^{-3}	$2.3^{+0.2}_{-0.2} \text{ cm}^{-3}$		
	$\log(N(\text{CO}))$	18.5 cm^{-2}	$19.2^{+0.9}_{-0.5} \text{ cm}^{-2}$		$\log(N(\text{CO}))$	18.8 cm^{-2}	$18.8^{+0.2}_{-0.2} \text{ cm}^{-2}$		
	J_{max}	6			J_{max}	5			
	CO cooling	$3.30 \times 10^{-9} \text{ W m}^{-2} \text{ sr}^{-1}$			CO cooling	$1.76 \times 10^{-9} \text{ W m}^{-2} \text{ sr}^{-1}$			
	$\tau_{\text{CO}_{1-0}}$	0.3			$\tau_{\text{CO}_{1-0}}$	4.7			
	$\tau_{\text{CO}_{2-1}}$	4.3			$\tau_{\text{CO}_{2-1}}$	13.7			
	$\tau_{\text{CO}_{3-2}}$	8.2			$\tau_{\text{CO}_{3-2}}$	22.9			
	$\tau_{\text{CO}_{4-3}}$	10.3			$\tau_{\text{CO}_{4-3}}$	24.5			
	$\tau_{\text{CO}_{6-5}}$	8.1			$\tau_{13\text{CO}_{1-0}}$	0.7			
			$\tau_{13\text{CO}_{2-1}}$	1.9					
3	T_K	175 K	139^{+76}_{-80} K	4	T_K	15 K	105^{+94}_{-71} K		
	$\log(n(\text{H}_2))$	3.3 cm^{-3}	$2.9^{+0.9}_{-0.6} \text{ cm}^{-3}$		$\log(n(\text{H}_2))$	7.0^* cm^{-3}	$4.4^{+1.8}_{-1.7} \text{ cm}^{-3}$		
	$\log(N(\text{CO}))$	19.3 cm^{-2}	$19.5^{+0.6}_{-0.6} \text{ cm}^{-2}$		$\log(N(\text{CO}))$	18.3 cm^{-2}	$19.6^{+0.7}_{-0.8} \text{ cm}^{-2}$		
	J_{max}	7			J_{max}	2			
	CO cooling	$6.77 \times 10^{-9} \text{ W m}^{-2} \text{ sr}^{-1}$			CO cooling	$1.09 \times 10^{-9} \text{ W m}^{-2} \text{ sr}^{-1}$			
	$\tau_{\text{CO}_{1-0}}$	1.5			$\tau_{\text{CO}_{1-0}}$	8.5			
	$\tau_{\text{CO}_{2-1}}$	6.8			$\tau_{\text{CO}_{2-1}}$	8.0			
	$\tau_{\text{CO}_{3-2}}$	14.5			$\tau_{\text{CO}_{3-2}}$	22.1			
	$\tau_{13\text{CO}_{2-1}}$	1.1			$\tau_{13\text{CO}_{2-1}}$	0.4			
5	T_K	15 K	41^{+108}_{-28} K	6	T_K	15 K	111^{+95}_{-77} K		
	$\log(n(\text{H}_2))$	4.0 cm^{-3}	$3.7^{+1.9}_{-0.5} \text{ cm}^{-3}$		$\log(n(\text{H}_2))$	4.3 cm^{-3}	$3.5^{+1.8}_{-0.9} \text{ cm}^{-3}$		
	$\log(N(\text{CO}))$	17.8 cm^{-2}	$17.9^{+0.6}_{-0.4} \text{ cm}^{-2}$		$\log(N(\text{CO}))$	17.3 cm^{-2}	$18.6^{+1.1}_{-2.4} \text{ cm}^{-2}$		
	J_{max}	2			J_{max}	3			
	CO cooling	$5.24 \times 10^{-10} \text{ W m}^{-2} \text{ sr}^{-1}$			CO cooling	$3.66 \times 10^{-10} \text{ W m}^{-2} \text{ sr}^{-1}$			
	$\tau_{\text{CO}_{1-0}}$	3.1			$\tau_{\text{CO}_{1-0}}$	0.6			
	$\tau_{\text{CO}_{2-1}}$	2.4			$\tau_{\text{CO}_{2-1}}$	1.4			
	$\tau_{\text{CO}_{3-2}}$	5.5			$\tau_{\text{CO}_{3-2}}$	0.9			
	$\tau_{13\text{CO}_{2-1}}$	0.2			$\tau_{13\text{CO}_{2-1}}$	$\ll 1$			
7	T_K	35 K	65^{+99}_{-43} K	8	T_K	35 K	140^{+76}_{-81} K		
	$\log(n(\text{H}_2))$	3.8 cm^{-3}	$4.1^{+1.8}_{-0.8} \text{ cm}^{-3}$		$\log(n(\text{H}_2))$	3.5 cm^{-3}	$2.9^{+0.4}_{-0.7} \text{ cm}^{-3}$		
	$\log(N(\text{CO}))$	15.0^* cm^{-2}	$17.8^{+2.5}_{-2.06} \text{ cm}^{-2}$		$\log(N(\text{CO}))$	17.8 cm^{-2}	$18.2^{+0.7}_{-0.7} \text{ cm}^{-2}$		
	J_{max}	3			J_{max}	4			
	CO cooling	$3.82 \times 10^{-10} \text{ W m}^{-2} \text{ sr}^{-1}$			CO cooling	$5.58 \times 10^{-10} \text{ W m}^{-2} \text{ sr}^{-1}$			
	$\tau_{\text{CO}_{1-0}}$	$\ll 1$			$\tau_{\text{CO}_{1-0}}$	0.6			
	$\tau_{\text{CO}_{2-1}}$	$\ll 1$			$\tau_{\text{CO}_{2-1}}$	3.5			
	$\tau_{\text{CO}_{3-2}}$	$\ll 1$			$\tau_{\text{CO}_{3-2}}$	4.2			
	$\tau_{\text{CO}_{4-3}}$	$\ll 1$			$\tau_{13\text{CO}_{2-1}}$	0.2			

Notes: χ^2 minimisation results list the best-fit models, defined as having the smallest χ^2 . Likelihood results list the median value and 68 per cent (1 σ) confidence levels of the marginalised probability distribution function of each model parameter. A star (*) indicates a value lying at the edge of the model grid. See Section 3 for more details.

dusty ISM. Regions 4, 5, 6 and 7 have weaker HI emission than that of the other regions (see Fig. 1).

Figure 4 shows the radial distribution of the molecular gas using the multiple tracers available. Two different components dominate: a highly concentrated central molecular core with a radius $\lesssim 1$ kpc, and a nearly flat lower surface brightness disc extending to large radii.

Of the 134 GMC candidates identified by Donovan Meyer et al. (2012) in the central 5 kpc of NGC 6946, only 30 are fully resolved in their data, and the others could be blends of GMCs smaller than the beam. Donovan Meyer et al. (2012) found that the most massive clouds ($> 10^7 M_\odot$) are located at the very centre of NGC 6946, and that clouds with masses $> 5 \times 10^5 M_\odot$ are preferentially found where the cloud density is highest (i.e. in the

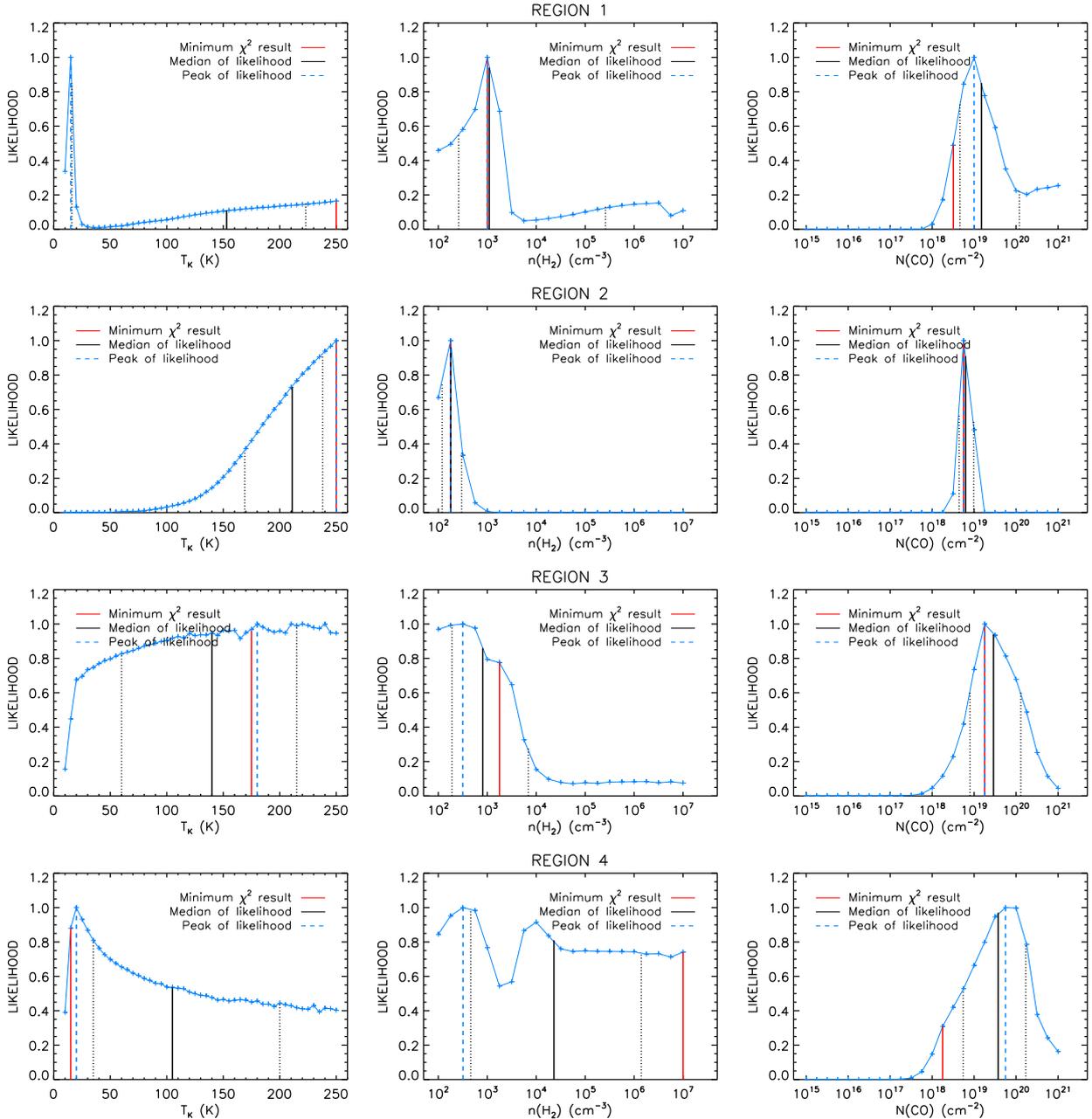


Figure 6. Marginalised probability distribution functions. For each region, the PDF of each model parameter marginalised over the other two is shown. The peak (most likely) and median values within the model grid are identified with dashed blue and solid black lines, respectively. The 68 per cent (1σ) confidence levels around the median are indicated by dotted black lines. The best-fit model from χ^2 minimisation is indicated by a solid red line.

spiral arms). They also showed that the GMC sizes range from 40 to 200 pc in the central 5 kpc, similar to the sizes found by Rebolledo et. al (2012) for 64 GMCs in the eastern part of the galaxy (50 to 150 pc). As our adopted common beam size of $31''.5$ corresponds to a linear diameter of ≈ 840 pc at the distance of NGC 6946, our beam will usually encompass an ensemble of (giant) molecular clouds. For each region, we thus estimate the total H_2 mass enclosed within our beam (M_{H_2}) using the CO-to- H_2 conversion factor ($X_{CO} = N(H_2) / S_{1-0}$) calculated by Donovan Meyer et al. (2012) from their 30 spatially-resolved GMCs in the centre of NGC 6946 (see Fig. 1): $X_{CO} = 1.2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$, consistent with the value assumed for the eastern GMCs by Re-

bolledo et. al (2012) and the average for the NGC 6946 disc reported by Sandstrom et al. (2012). Sandstrom et al. (2012) do report a depression of the X_{CO} value in the very centre of NGC 6946 (i.e. within a radius of 1.2 kpc), but since all our regions are well outside of this our calculations should be unaffected. Considering the adopted beam, distance, and X_{CO} factor, we thus obtain

$$\frac{M_{H_2}}{M_{\odot}} = 3.6 \times 10^5 \left(\frac{S_{1-0}}{\text{K km s}^{-1}} \right). \quad (7)$$

The resulting total H_2 mass and beam-averaged H_2 column density of each region are listed in Table 6.

The gas complex in region 1 has the highest CO(1-0) flux and

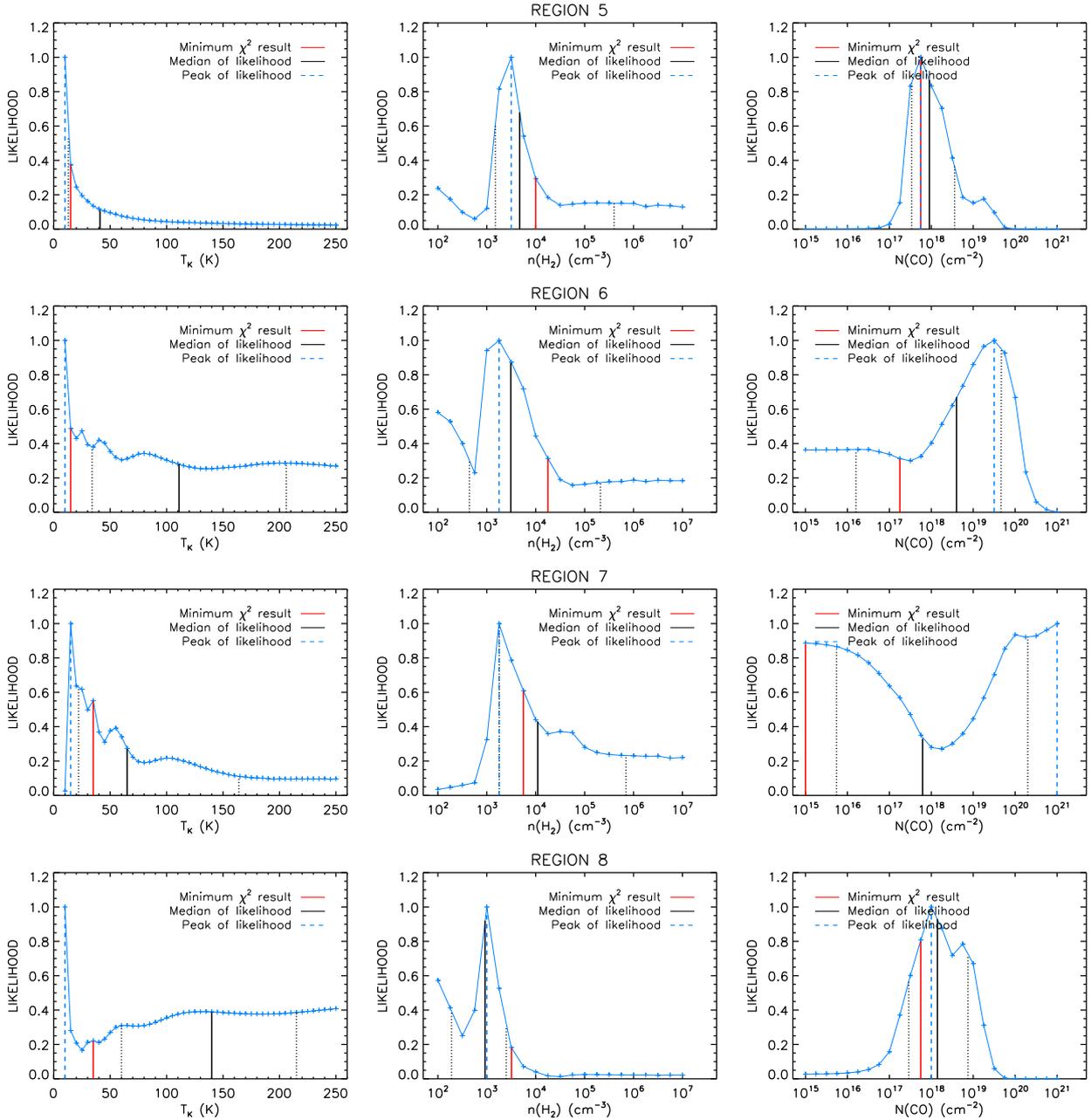


Figure 6. Continued.

Table 6. Total H₂ masses and beam-averaged H₂ column densities.

Region	M_{H_2} (M_{\odot})	$N(\text{H}_2)$ (cm^{-2})
1	$3.1 \pm 0.1 \times 10^6$	$1.1 \pm 0.1 \times 10^{21}$
2	$2.9 \pm 0.2 \times 10^6$	$9.9 \pm 0.5 \times 10^{20}$
3	$2.7 \pm 0.2 \times 10^6$	$9.0 \pm 0.5 \times 10^{20}$
4	$1.7 \pm 0.2 \times 10^6$	$5.7 \pm 0.5 \times 10^{20}$
5	$2.1 \pm 0.1 \times 10^6$	$6.9 \pm 0.4 \times 10^{20}$
6	$1.7 \pm 0.2 \times 10^6$	$5.7 \pm 0.5 \times 10^{20}$
7	$1.3 \pm 0.2 \times 10^6$	$4.4 \pm 0.5 \times 10^{20}$
8	$2.6 \pm 0.2 \times 10^6$	$8.8 \pm 0.5 \times 10^{20}$

thus total H₂ mass ($3.1 \pm 0.1 \times 10^6 M_{\odot}$), while the gas in the

inter-arm region 7 (farthest from the galaxy centre) has the lowest mass ($1.3 \pm 0.2 \times 10^6 M_{\odot}$). Having said that, the total gas mass does not vary much from region to region (factor ≈ 3), and for the 8 regions studied it does not vary linearly with distance from the galaxy centre (as hinted from Fig. 4). All regions have total H₂ masses $> 5 \times 10^5 M_{\odot}$.

As shown in Table 4, the beam-corrected velocity-integrated line intensity of the CO(2-1) transition is higher than that of all other transitions observed in all regions (including region 8 within the uncertainties). While R_{21} (the CO(2-1)/CO(1-0) line ratio) is higher than unity in all regions, all other line ratios considered (with respect to the ground state) are less than unity. Interestingly, R_{31} (the CO(3-2)/CO(1-0) line ratio) is the only line ratio that is very similar in all regions. Where we have measurements, the isotopo-

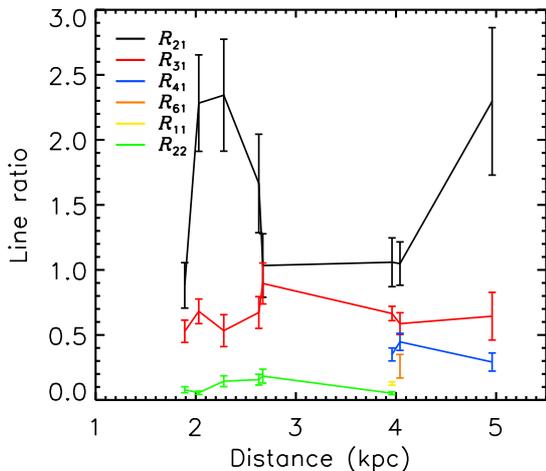


Figure 7. Beam-corrected line ratios as a function of radius in NGC 6946. The line ratios are color-coded and defined in the text (see Section 4.1).

logue transitions $^{13}\text{CO}(1-0)$ and $^{13}\text{CO}(2-1)$ are 5–20 times fainter than their parent lines. Anticipating some of our modeling results (see Table 5 and § 5), one also notices that the line ratios of regions 1, 2 and 3, those of regions 4, 5, and 6, and lastly those of regions 7 and 8 are similar (although not identical) to each other, suggesting similar molecular gas physical conditions in each group of regions.

Figure 7 shows the beam-corrected velocity-integrated line ratios (as listed in Table 4) as a function of radius, from ≈ 2 (region 8) to 5 kpc (region 7). The well-sampled radial profiles of R_{31} , R_{41} (the $\text{CO}(4-3)/\text{CO}(1-0)$ line ratio) and R_{22} (the $^{13}\text{CO}(2-1)/\text{CO}(2-1)$ line ratio) show little variation with radius ($R_{31} \approx 0.7$, $R_{41} \approx 0.4$ and $R_{22} \approx 0.1$). R_{61} (the $\text{CO}(6-5)/\text{CO}(1-0)$ line ratio) and R_{11} (the $^{13}\text{CO}(1-0)/\text{CO}(1-0)$ line ratio) were measured in two different regions only (see Fig. 7). R_{31} is less than that at the centre of our own Galaxy, but higher than in the Milky Way arms (Oka et al. 2007).

The R_{21} ratio does vary across the radial range probed ($R_{21} \approx 1.0$ – 2.5), but it is always greater than 1.0. Koda et al. (2012) studied the spatial variations of R_{21} in both the arms and inter-arm regions of M 51 (with a spatial resolution comparable to ours), and found that $R_{21} > 0.7$ in the spiral arms (often 0.8–1.0). They also showed that R_{21} generally increases with SF activity (as traced by $f_{24\mu\text{m}}$ and $f_{24\mu\text{m}}/S_{\text{CO}(1-0)}$). This is opposite to what we observe in NGC 6946, since regions 4, 5 and 6 (and 7) have the highest R_{21} ratios but relatively low SF activity (see Table 4 and § 5). However, Koda et al. (2012) do note that high values of R_{21} are also present with low $f_{24\mu\text{m}}$, $S_{\text{CO}(1-0)}$ and $f_{24\mu\text{m}}/S_{\text{CO}(1-0)}$ values, at the upstream edges of the 24 μm spiral arms (indicating dense gas that could potentially form massive OB stars). As regions 4, 5 and 6 (and 7) in NGC 6946 are located in the more flocculent spiral arms and inter-arm regions, the $\text{CO}(1-0)$ velocity-integrated line intensity is lower there compared to other regions, and this could be the cause of the high R_{21} ratios observed. These regions may therefore have dense but not very warm pre-SF gas (as suggested later by our models; see Table 5).

4.2 Modeling results

4.2.1 Molecular ISM physical conditions

The physical parameters estimated for each region are listed in Table 5, from both the χ^2 minimisation and likelihood methods. Overall, across the 8 regions considered, the modeled beam-averaged kinetic temperature T_{K} ranges from 15 to 250 K (the whole range of models considered), while the molecular hydrogen number volume density $n(\text{H}_2)$ and the CO number column density $N(\text{CO})$ vary by a factor of ≈ 100 (although regions 4 and 7 possibly have more extreme values of $n(\text{H}_2)$ and $N(\text{CO})$, respectively).

In some regions, one of the best-fit model parameters lies at the edge of the model grid (temperature in regions 1 and 2, H_2 number density in region 4 and CO column density in region 7; see Fig. 5 and Table 5). However, as also shown in Figure 5, those χ^2 minima exist within a much broader range of good models, and the likelihood method (see Fig. 6 and Table 5) yields reasonable ranges of probable parameters values. Those parameters are thus simply ill-constrained. We come back to this issue below.

The hottest and most tenuous molecular ISM is found in regions 1 and 2, with the highest numbers of H II regions and GMCs among the regions studied (see Fig. 1). Interestingly, Rebollo et al. (2012) concluded that while the clouds located in the eastern part of NGC 6946 have properties independent of the location in the disc, some arm clouds are more massive, have a broader line width and have a higher SFR. In particular, they found three such clouds located within our regions 1 and 2 (regions 6, 7 and 11 in their work; see also their Fig. 2). Regions 1 and 2 therefore appear to have particularly extreme properties. Our model results also suggest a fairly hot and tenuous ISM in region 3 (similar to regions 1 and 2), with the highest number of SNRs (Fig. 1).

The coldest and densest molecular ISM is located in regions 4, 5 and 6. Interestingly, the physical conditions in the inter-arm regions 7 and 8 are intermediate, although more similar to those of regions 4, 5 and 6 (if somewhat warmer) than those of regions 1, 2 and 3.

As shown in Figure 8, the best-fit CO column density and total volume density are not clearly correlated. If anything, excluding region 4, there is a slight anti-correlation. A stronger anti-correlation exists between T_{K} and $n(\text{H}_2)$ (again excluding region 4), implying a weak correlation between $N(\text{CO})$ and T_{K} . These trends suggest a slight decrease of the CO abundance when the temperature decreases and the volume density increases. Although speculative, this could be interpreted as the effects of depletion processes and freeze-out onto grains during cloud collapse. However, without confirmation from additional molecules, such as N_2H^+ and/or methanol, known for tracing well gas phases experiencing or having experienced freeze-out processes, we only point out the reader a potential trend that regions 5, 6 and 8 may have more collapsing clouds/cores included in its observed beam than the other regions.

As each region is located at a different distance from the galactic centre, we can probe radial variations of the three main derived physical parameters in NGC 6946 (Fig. 8). As might naively be expected, the total volume density $n(\text{H}_2)$ tends to decrease with radius (excluding region 4). However, somewhat counter-intuitively (but expected from the aforementioned correlations), $N(\text{CO})$ and T_{K} tend to increase with radius (excluding region 7).

Having said that, since we only probed particular star-forming regions in the spiral arms and inter-arms of NGC 6946 where observations of multiple lines of CO are available, the aforementioned relationships among the molecular gas physical parameters can not be generalised to the entire disc of the galaxy, even less to spirals

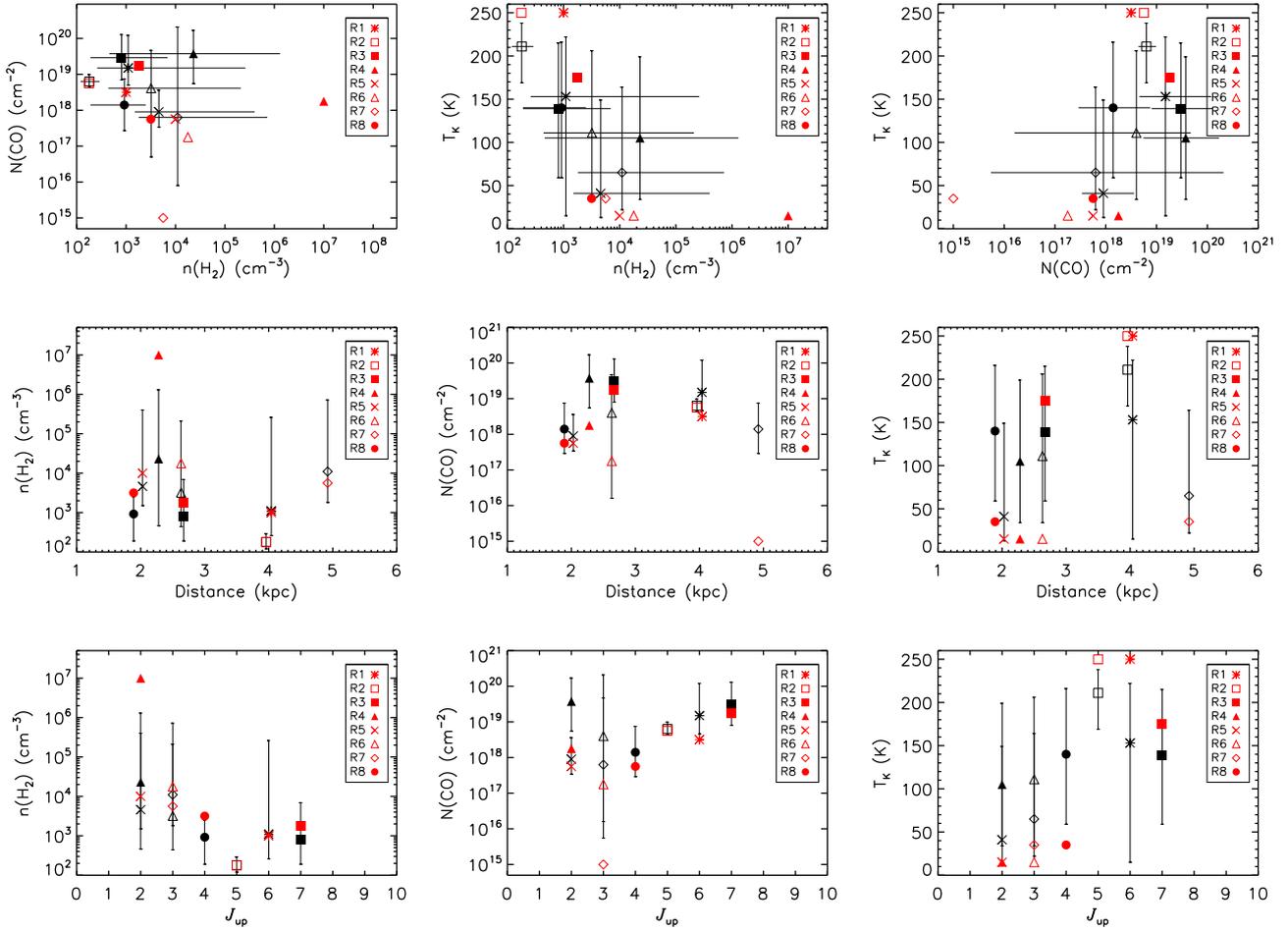


Figure 8. Top: Correlations between the best-fit parameters (T_K , $n(\text{H}_2)$ and $N(\text{CO})$) of the 8 regions studied. Middle: Same physical parameters as a function of galactocentric radius. Bottom: Same physical parameters as a function of the predicted J_{max} . Red symbols show the results from the χ^2 analysis. Black symbols with error bars represent the median of the marginalised probability distribution function of each model parameter, along with the 68 per cent (1σ) confidence levels (see Table 5).

in the nearby universe generally. In fact, excluding regions 1, 2 and 3 (with the highest SF activity and highest T_K and $N(\text{CO})$) eradicats all the correlations (see Fig. 8). The relationships among the physical parameters presented in Figure 8 could therefore be biased by selection effects. Only a homogenous survey of multiple molecular lines across the entire disc of NGC 6946 could provide demonstratively unbiased results.

As hinted above, it is interesting to compare the probability distribution functions of the three main physical parameters (marginalised over the other two) with the simple χ^2 minimisation results, as done in Figure 6. $N(\text{CO})$ is generally the best constrained parameter, with single-peaked Gaussian PDFs and thus good agreement between the peak and median of the likelihood. Similarly, the best-fit model (in a χ^2 sense) is generally contained within the 68 per cent (1σ) confidence levels (it is in all but one region at the 2σ level). The situation is less satisfactory for $n(\text{H}_2)$ and particularly for T_K , due to their degeneracy (i.e. the characteristic “banana”-shaped $\Delta\chi^2$ contours or inverse $n(\text{H}_2)$ – T_K relationship; see Fig. 5 and Appendix C of van der Tak et al. 2007). The PDFs for $n(\text{H}_2)$ and T_K typically have a small peak within a rather broad and flat likelihood distribution. Unsurprisingly, the best-fit model is thus again generally contained within the 68 per cent

confidence levels (except in a few cases where the best-fit model is at the edge of the grid and thus unreliable). However, this also highlights the fact that, although generally well-defined, the best-fit model is often only slightly more likely (i.e. better fitting) than a host of other models spanning a wide range of physical parameters. This questions the wisdom of considering the best-fit model alone as a reasonable approximation of the true physical conditions, a practice adopted in many studies. The confidence intervals listed in Table 5 are a first step at concisely quantifying the uncertainties.

In Fig. 9, we show the modeled optical depth τ of the CO lines as a function of the upper J level of the transition J_{up} , this for the best-fit model of each region. All regions except region 7 (which also has the lowest best-fit CO number column density) have $\tau > 1$ for at least one transition, indicating that we only see the outermost layers of the clouds in those transitions. The optical depth distributions are qualitatively similar to the beam-averaged total intensity distributions, in the sense that both peak at roughly the same transitions. Indeed the optical depth is maximum at $J_{\text{up}} = 5$ –7 in regions 1, 2 and 3, while it peaks at $J_{\text{up}} = 2$ –4 in the other regions. A similar trend has also been observed for high density tracers by Goldsmith & Langer (1999).

The beam-averaged total CO cooling rate of each region was

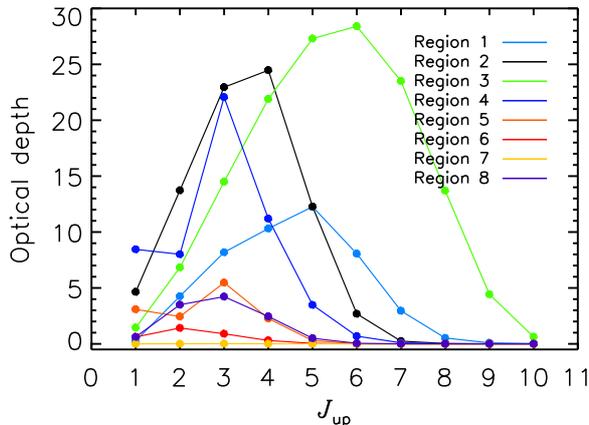


Figure 9. Optical depth distributions. For each region (colour-coded), the optical depth of the CO line for the best-fit model is shown as a function of the upper J level of the transition (up to $J=10-9$).

also estimated from the best-fit model, summing all CO transition intensities up to $J_{\text{up}} = 10$. The results are listed in Table 5. As expected, regions 1, 2 and 3 have CO cooling rates ≈ 10 times higher than those of the other regions. They are the most powerful emitting regions, encompassing the highest number of H II regions and GMCs (regions 1 and 2) and the highest number of SNRs (region 3), all indicating young stellar populations (see Fig. 1). The other regions, where the ISM is colder and denser, have lower CO cooling rates.

4.2.2 Spectral line energy distributions

We plot the CO spectral line energy distribution (SLED) of the best-fit model of each region in Figure 10, overlaid with the observed data points. Also shown are the SLED ranges allowed by the 1σ confidence level on the best-fit model, as well as the SLED of the most likely model. By construction, the models are in good agreement with the data. The modeled integrated line intensities generally decrease with increasing upper energy level J_{up} , but the beam-averaged total intensities peak at intermediate transitions.

The location of the SLED turnover (J_{max}) is interesting, as it provides information on the SF activity level, and it is listed in Table 5 for each region. In the heavily star-forming galaxy APM 08279+5255 at redshift $z \approx 4$, $J_{\text{max}} = 9$ (Weiss et al. 2007). In the centre of local starbursting galaxies such as Henize 2-10, NGC 253 and M 82, $J_{\text{max}} \approx 6-7$ (Bayet et al. 2004; Weiß et al. 2005), while it is ≈ 3 in molecular streamers/outflows around M 82’s central molecular disc (Weiß et al. 2005). $J_{\text{max}} \approx 4$ in the centre of our own Galaxy, whereas it is ≈ 3 in the Galactic plane at longitudes $2^\circ.5 < l < 32^\circ.5$, where CO emission is much weaker than in the central regions (Fixsen, Bennett & Mather 1999). On the other hand, the Orion Bar photodissociation region in the Milky Way disc shows extreme star formation activity, with $J_{\text{max}} \approx 13$ (Habart et al. 2010).

In NGC 6946, the predicted turnover takes place at $J_{\text{max}} = 5-7$ in regions 1, 2 and 3 (hot and tenuous ISM), while $J_{\text{max}} = 2-4$ in the other regions (colder and denser ISM). From the above discussion, this suggests more intense SF activity in regions 1, 2 and 3 compared to the other regions. In fact, SF in regions 1, 2 and 3 appears more extreme than that in the Galaxy centre.

As visible in Figure 10, an inflection point is present at $J_{\text{up}} = 3$ in the SLED of region 4, where the CO(3-2) integrated line intensity is slightly smaller than that of both CO(2-1) and CO(4-3). Although we refer the reader to van der Tak et al. (2007) for more details on the relation between opacity and line intensity, we note that the opacity in region 4 peaks at $J_{\text{up}} = 3$ and is more than twice that for $J_{\text{up}} = 2$ and 4 (see Fig. 9), causing the apparent reduction of the CO(3-2) integrated line intensity. Since the low- J trend is more consistent with the observed lines and the best-fit physical parameters (see Fig. 10), we adopt $J_{\text{max}} = 2$ for region 4.

Perhaps unsurprisingly, the strongest correlation of J_{max} with the molecular ISM physical conditions is that with the kinetic temperature T_{K} (see Fig. 8). Indeed, J_{max} is maximum for regions 1, 2 and 3, with the highest T_{K} , while it is lowest for regions 4, 5 and 6, with the lowest T_{K} (regions 7 and 8 are, again, intermediate). As seen in Figure 8 and expected from the aforementioned correlations among the physical parameters, $N(\text{CO})$ also shows a correlation with J_{max} but it is relatively weak (and region 7 is an outlier), whereas $n(\text{H}_2)$ shows an anti-correlation (and region 4 is an outlier). It therefore seems that in the regions where the turnover takes place at high $J_{\text{max}} (> 4)$, the gas tends to be hot (high T_{K}) and diffuse (low $n(\text{H}_2)$) with a high CO column number density, while in regions where the turnover takes place at low $J_{\text{max}} (\leq 4)$, the gas is cold and dense with a relatively low CO column number density.

5 DISCUSSION

5.1 Star formation activity

A variety of heating mechanisms of the molecular ISM are present in galaxies, including far-ultraviolet (FUV) radiation (from massive stars and active galactic nuclei), dust-gas collisions, cosmic rays, mechanical heating (e.g. turbulence) and chemical heating (see, e.g., Röllig et al. 2007). But which heating mechanisms dominate in the regions studied? More specifically, how does SF feedback regulate the physical conditions of the ISM? From both observational and theoretical arguments, there must be a connection between the gas physical conditions and the immediate environment of the regions, such as the presence SNRs, H II regions, and HI holes. In this section, we therefore discuss the physical properties derived from our models in relation to the environmental characteristics of the regions studied, and compare our results in the spiral arms and inter-arm regions with previous results for the centre of NGC 6946.

Overlaid on H α and HI images, some of the features present in NGC 6946 were illustrated in Figure 1: HI holes (Boomsma et al. 2008), GMCs (Donovan Meyer et al. 2012; Rebolledo et al. 2012), H II regions (Bonnarel et al. 1986), giant H II complexes (van der Kruit et al. 1977), CO complexes (Rebolledo et al. 2012) and SNRs (Matonick & Fesen 1997; Lacey & Duric 2001). All the regions studied in this paper are associated with one or more of these features.

Of the 62 SNRs detected in NGC 6946 (both optically and in the radio), 40 are associated with spiral arms while 22 are located in inter-arm regions. Lacey & Duric (2001) argued that the arm SNRs (mostly radio-bright) have massive progenitors (Population I stars) and explode as Type II/Ib/Ic supernovae. Indeed, with short lifetimes, many of the progenitors will explode inside or close to their parent molecular cloud. Lacey & Duric (2001) in fact showed that the radio-bright SNRs are likely associated with H II and star-forming regions, an association borne out by Figure 1. On the other

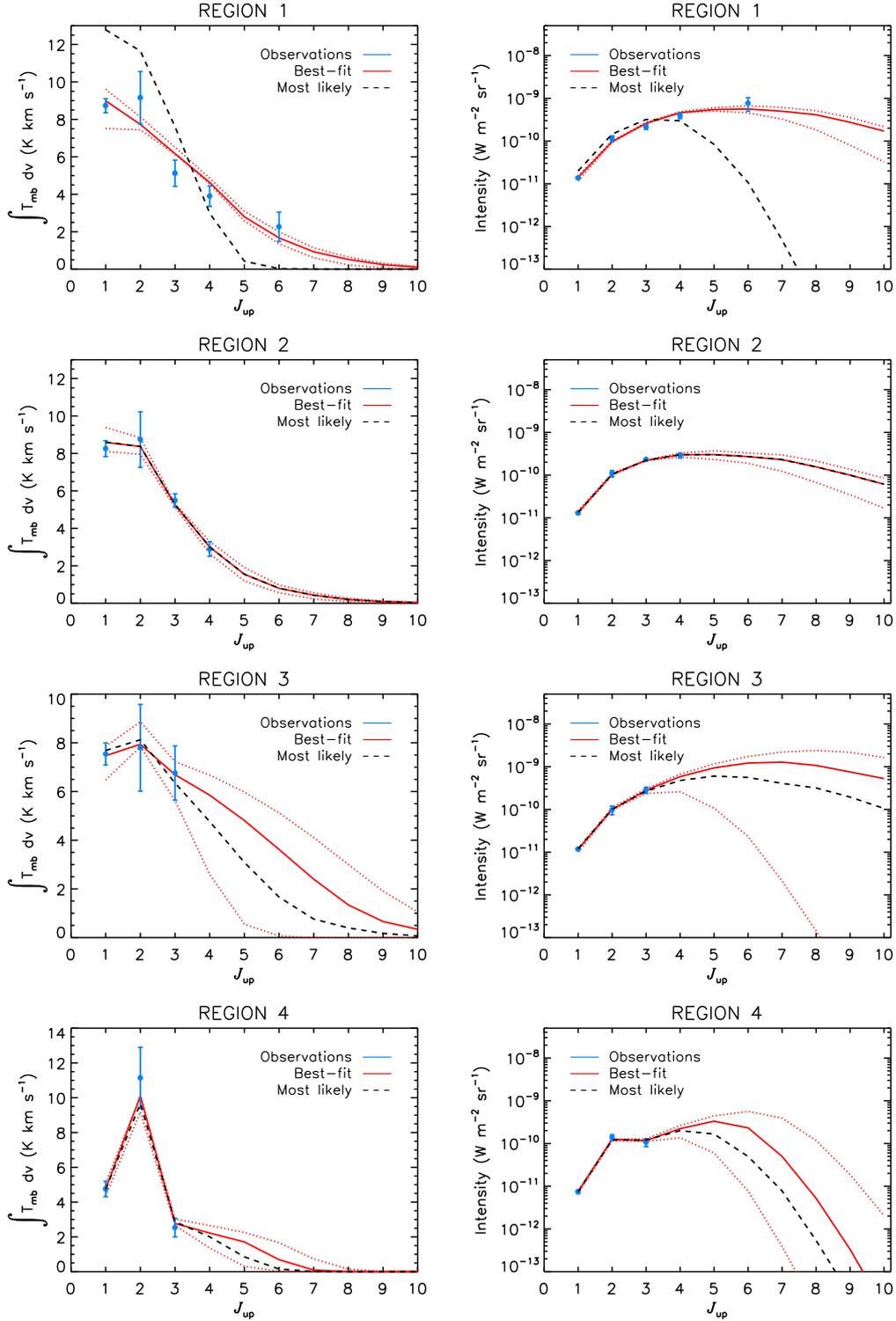


Figure 10. Spectral line energy distributions. For each region, the integrated line intensity S (left) and beam-averaged total intensity per unit area I (right) are shown as a function of the upper J level of the transition (up to $J=10-9$). The solid red line shows the best-fit model, while the dotted red lines delineate the range of possible SLEDs encompassed by the 1σ confidence level on the best-fit model (the darkest zone in the $\Delta\chi^2$ contour maps of Fig. 5). The dashed black line shows the SLED corresponding to the most likely model. Blue circles with error bars are our observations.

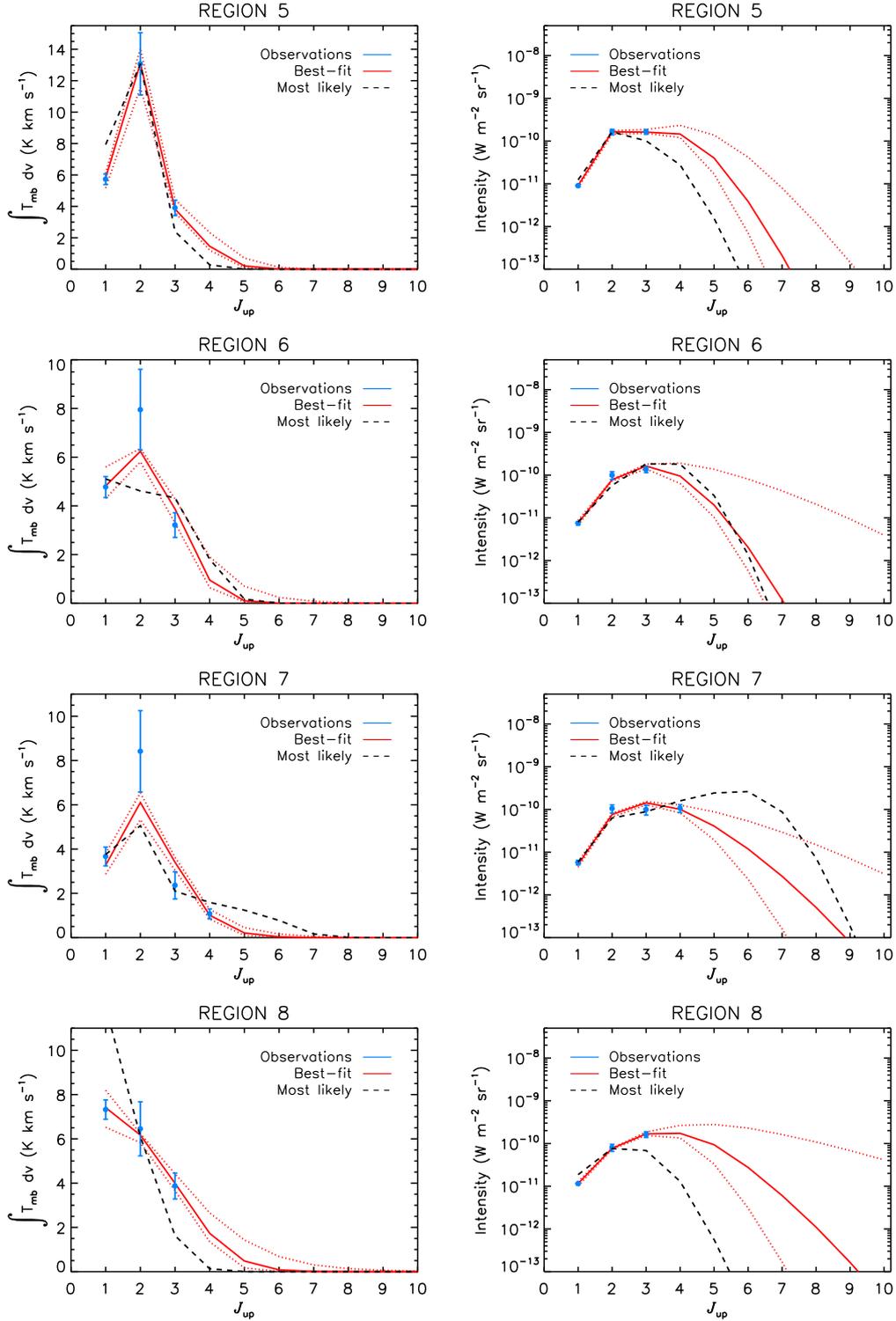


Figure 10. Continued.

hand, the inter-arm SNRs (mostly optically-selected) are thought to have Population II progenitors (Lacey & Duric 2001).

In the galaxy M33, most radio-emitting SNRs have a diameter ranging from 20 to 80 pc (Duric et al. 1995). In the Galaxy, the bulk of the 47 SNRs with a distance determination in the catalogue of

Green (2012) have a diameter between 10 and 100 pc¹. However, stellar winds and/or diffuse ionised gas can help create shells with diameters $\gtrsim 100$ pc (Matonick & Fesen 1997). As cosmic rays

¹ <http://www.mrao.cam.ac.uk/projects/surveys/snr/>

produced by SN explosions and shocks can travel large distances in low density environments (weak absorption), where they heat up their surroundings (Meijerink et al. 2011), we can expect that the average temperature will be higher in low density environments than in high density ones.

Of course, UV radiation from short-lived massive stars is generally believed to be the main stellar feedback mechanism affecting GMCs (e.g. Colin et al. 2013 and references therein). Indeed, simulations show that massive stars ($M_* \gtrsim 20 M_\odot$) can locally disrupt their surrounding clouds via photoionisation, creating H II regions and potentially triggering SF at new locations in the clouds.

Spiral arms clearly lead to an increase in the number of cloud collisions (Dobbs 2008). Classical grand-design spiral structures are thought to form from perturbations due to bars or companions, while flocculent structures develop from local gravitational instabilities (see; e.g., Dobbs & Bonnell 2008). NGC 6946 is a flocculent galaxy, with characteristic broken spiral arms. For the formation of GMCs, and thus of stars, the local gravitational instabilities seen in flocculent galaxies are therefore likely to be more important than global spiral dynamics.

In the following sub-sections, our results are therefore discussed in view of the environment and SF activity in each region, grouping regions with similar characteristics. Specifically, we consider regions 1, 2 and 3 (intense SF activity), regions 4, 5 and 6 (low SF activity), and regions 7 and 8 (inter-arm regions and intermediate SF activity). We also compare the gas physical properties previously found in the centre of NGC 6946 with our own results in the arm and inter-arm regions.

5.2 Regions 1, 2 and 3

As shown in Figure 1, regions 1 and 2 are associated with giant H II complexes, encompassing many H II regions that each indicate the presence of OB stars and thus FUV radiation. In particular, as mentioned before, region 1 has the highest number of H II regions of all the regions studied. The H I hole associated with region 2 may well have been created by supernova explosions, as three SNRs are located near the centre of the hole. Regions 1 and 2 are also associated with some of the main star-forming regions previously studied by Murphy et al. (2010, 2011) using 33 GHz free-free emission, a standard tracer of SF. Although not part of a catalogued giant H II complex, region 3 nevertheless lies in an important spiral arm and harbours many H II regions and SNRs (see Fig. 1).

The environment of and features present in regions 1, 2 and 3 are thus similar, both indicating a high level of SF activity (slightly higher in region 1 than 2, and in region 2 than 3). Our modeling results reflect this, as the gas physical conditions are indeed similar and indicate significant heating of the molecular ISM in all three regions (see Table 5), presumably from FUV radiation and stellar winds associated with OB stars (and potentially cosmic rays from supernovae): high kinetic temperature T_K and low H_2 number volume density $n(H_2)$ despite a high opacity.

We note that Walsh et al. (2002) also carried out LVG modeling of region 2 but found $T_K = 15$ K, at the opposite end of the range of possible values and firmly ruled out here ($n(H_2)$ and $N(CO)$ are also different, but less so). While worrying at face value, this large temperature discrepancy probably arises from the different transitions used to determine the best-fit model. In particular, Walsh et al. (2002) did not use relatively high- J transitions of CO, like the CO(4-3) line used here, that require relatively high temperatures to be excited.

5.3 Regions 4, 5 and 6

Regions 4 and 5 are very close to each other and overall significantly (see Fig. 1), so as expected the physical conditions suggested by our modeling are very similar (see Table 5). The best-fit $n(H_2)$ is substantially higher for region 4 (at the edge of our model grid), but the likelihood shows that this parameter is rather ill-constrained. In addition, the molecular ISM physical conditions derived in region 6 are very similar to those of regions 4 and 5. This is easily understood, as all three regions are located in rather similar environments (flocculent spiral arms; see Fig. 1).

Compared to regions 1–3, regions 4–6 have much lower temperatures and higher densities. This can be again explained by considering their environment and observed features. Regions 4 and 5 do encompass some H II regions (and region 4 has one catalogued SNR), but not as many as regions 1–3. Similarly, region 6 has a small number of H II regions, SNRs and GMCs at its edge, but none within our adopted beam (see Fig. 1). It is also largely co-spatial with a large H I hole (≈ 900 pc diameter). It is thus likely that, while SF likely took place in the past and the potential for future SF is high, current SF activity is relatively mild in regions 4–6 (compared to regions 1–3), and this is reflected in the current molecular gas physical conditions.

5.4 Regions 7 and 8

Regions 7 and 8 are located in the inter-arm regions of NGC 6946, respectively to the NE and SW of the galaxy centre (see Fig. 1). Interestingly, while one would naively expect the lowest SF activity of all our regions, and correspondingly the lowest ISM temperatures and highest densities, this is not the case. Our models reveal physical conditions (T_K , $n(H_2)$ and $N(CO)$) that are intermediate between those of regions 1–3 and those of regions 4–6 (see Table 5).

While we do not have a truly satisfying explanation for this, we suspect that SF activity is simply not as low as expected in those two regions. Indeed, region 7 lies at the edge of a major spiral arm and has some H II regions and GMCs, while region 8 harbours one particularly large GMC (spatially) and a few H II regions (at the centre of the GMC; see Fig. 1). As there is no SNR in either region, it is possible that the SF activity in those regions is simply lower or is just beginning.

In any case, SF activity in regions 7 and 8 may well be higher than naive expectations for the general inter-arm medium by construction, as the regions studied here were necessarily chosen to contain some molecular clouds.

5.5 Spiral arms vs. galaxy centre

Many studies have probed the molecular gas physical conditions at the centre of NGC 6946, where there is a small bar (Ball et al. 1985; Weliachew et al. 1988; Bonnarel et al. 1988; Ishizuki et al. 1990; Regan & Vogel 1995) and starburst activity (Engelbracht et al. 1996). Israel & Bass (2001) concluded that there are at least two molecular components in the central region, a warm ($T_K = 30$ – 60 K) and dense ($n(H_2) = 3$ – 10×10^3 cm $^{-3}$) component and a more tenuous ($n(H_2) \leq 10^3$ cm $^{-3}$) and hotter ($T_K = 100$ – 150 K) component. Walsh et al. (2002) and Bayet et al. (2006) also probed the gas physical properties at the centre using LVG modeling. Walsh et al. (2002) found $T_K = 40$ K for the gas kinetic temperature at the centre, while Bayet et al. (2006) found $T_K = 130$ K. The higher temperature found by Bayet et al. (2006) may be caused

by the high- J transition of CO used (CO(6-5)), requiring a higher temperature to be excited. The densities derived are however very similar ($n(\text{H}_2) = 10^{3.2-10^{3.3}} \text{ cm}^{-3}$).

It is interesting to compare the properties of the molecular gas present at the centre of the galaxy with those of the gas in the spiral arms and inter-arm regions. As discussed above (see also Table 5), our results indicate three different media across the regions studied; hot and tenuous (regions 1–3), cold and dense (regions 4–6), and intermediate (warm; inter-arm regions 7–8). Regions 1–3 have hot and relatively tenuous molecular gas similar to the hot and tenuous central component identified by Israel & Bass (2001). This is likely related to intense SF activity and associated shocks from SNRs (both heating up and sweeping up the gas). The inter-arm regions 7–8 have warm and dense molecular gas similar to that of the central warm and dense component identified by Israel & Bass (2001). Unsurprisingly, the cold and dense gas in regions 4–6 does not match any of the central molecular gas properties.

6 CONCLUSIONS

In this paper, we have provided the most complete CO survey of the nearby galaxy NGC 6946 ever performed, including for each of the 8 regions studied at least 4 transitions of CO. The data presented in Table A1 and Appendix B further cover a much broader area of NGC 6946, and should be useful for diverse projects investigating its SF activity. From the observations and gas physical parameters derived for each region, our main results can be summarised as follows:

(i) The CO(2-1) map indicates that molecular gas is ubiquitous across NGC 6946 but is concentrated along the spiral arms, with a regular velocity field. The CO(3-2) data reveal two compact ‘hotspots’ (very active star-forming regions) in the eastern spiral arms (regions 1 and 2), where the gas is also bright at $\text{H}\alpha$, $24 \mu\text{m}$, $850 \mu\text{m}$ and 6.2 cm .

(ii) The radial profiles of the different CO transitions probed (eastward from the centre up to $\approx 4 \text{ kpc}$) reveal the likely presence of two components: a highly-peaked molecular core and a nearly flat lower surface brightness extended disc.

(iii) While the beam-corrected line ratio R_{21} varies significantly across NGC 6946 (≈ 1 to 2.5), the other ratios are more constant: $R_{31} \approx 0.7$, $R_{41} \approx 0.4$ and $R_{22} \approx 0.1$.

(iv) According to LVG modeling, selected regions in NGC 6946 have a large variety of physical conditions (see Table 5). Overall, the gas kinetic temperature T_{K} ranges from 15 to 250 K , the H_2 number volume density $n(\text{H}_2)$ ranges from $10^{2.3}$ to $10^{7.0} \text{ cm}^{-3}$, and the CO number column density $N(\text{CO})$ ranges from $10^{15.0}$ to $10^{19.3} \text{ cm}^{-2}$.

(v) Comparing these physical properties with star formation-related environmental characteristics such as the presence of SNRs, HI holes, HII regions/complexes and GMCs, the regions probed can naturally be grouped into 3 broad categories. First, regions 1, 2 and 3 are hotter and more tenuous than the other regions. They also show the strongest signs of SF activity, most likely driven by young massive OB stars. FUV radiation and stellar winds therefore likely dominate the heating and excitation of the molecular ISM in these regions, with a possible contribution from SNR-related cosmic rays in region 3. Second, regions 4, 5 and 6 are colder and denser than the other regions. They also likely harbour less intense SF activity, with fewer SF-related characteristic features. Third, the inter-arm regions 7 and 8 reveal intermediate gas physical properties, suggesting (somewhat surprisingly) equally intermediate SF activity.

(vi) The turnovers of the predicted SLEDs indicate that in regions where the turnover takes place at high J ($J_{\text{max}} > 4$), T_{K} and $N(\text{CO})$ are high whereas $n(\text{H}_2)$ is relatively low. On the other hand, in regions where the turnover takes place at low J ($J_{\text{max}} \leq 4$), T_{K} and $N(\text{CO})$ are low whereas $n(\text{H}_2)$ is relatively high.

(vii) Based on the predicted SLEDs, some extra-nuclear regions (i.e. regions 1, 2 and 3) have a SF activity comparable to that seen at the centre of NGC 6946, much higher than that at the centre of our own Galaxy. The SF activity in the other regions studied is however comparable to that at the centre of the Milky Way.

ACKNOWLEDGEMENTS

The authors thank S. Kaviraj for useful discussions on the likelihood method and F. van der Tak for very useful discussions on the radiative transfer code RADEX. ST gives special thanks to David Rebolledo and Jennifer Donovan Meyer for providing their GMC data. ST was supported by the Republic of Turkey, Ministry of National Education, and The Philip Wetton Graduate Scholarship at Christ Church. EB and MB were partially supported by an Oxford Fell Fund award during the course of this work, and by STFC rolling grant Astrophysics at Oxford ST/H002456/1. ST and MB thank the Department of Physics at Nagoya University for its hospitality during a sabbatical visit. The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013/) under grant agreement No 229517. This research also made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

- Aladro R., Martín-Pintado J., Martín S., Mauersberger R., & Bayet E., 2011, *A&A*, 525, 89
 Arp H., 1966, *ApJS*, 14, 1
 Ball R., Sargent A. I., Scoville N. Z., Lo K.Y., Scott S. L., 1985, *ApJ*, 298, 21
 Bayet E., Gerin M., Phillips T. G., Contursi A., 2004, *A&A*, 427, 45
 Bayet E., Gerin M., Phillips T. G., Contursi A., 2006, *A&A*, 460, 467
 Bayet E., Aladro R., Martín S., Viti S., Martín-Pintado J., 2009, *ApJ*, 707, 126
 Bayet E. et al., 2013, *MNRAS*, 432, 1742
 Beck R., Hoernes P., 1996, *Nature*, 379, 47
 Bianchi S., Davies J. J., Alton P. B., Gerin M., Casoli F., 2000, *A&A*, 353, 13
 Boomsma R., Oosterloo T. A., Fraternali F., van der Hulst J. M., Sancisi R., 2008, *A&A*, 490, 555
 Boomsma, R. 2007, Ph.D. Thesis, Kapteyn Astronomical Institute, University of Groningen
 Bonnarel F., Boulesteix J., Marcelin M., 1986, *A&AS*, 66, 149
 Bonnarel F., Boulesteix J., Georgelin Y. P., Lecoarer E., Marcelin M., Bacon R., Monnet G., 1988, *A&A*, 189, 59
 Braun R., Oosterloo T. A., Morganti R., Klein U., Beck, R., 2007, *A&A*, 461, 455
 Colin P., Vazquez-Semadeni E., Gomez Gilberto C., 2013, arXiv:1304.1570

- de Blok W. J. G., Walter F., Brinks E., Trachternach C., Oh S. H., Kennicutt R. C., 2008, *AJ*, 136, 2648
- DeGioia-Eastwood K., Grasdalen G. L., Strom A. E., Strom K. M., 1984, *ApJ*, 278, 564
- de Jong T., Dalgarno A., Chu S. I., 1975, *ApJ*, 199, 69
- Dobbs C. L., & Bonnell I. A., 2008, *MNRAS*, 385, 1893
- Dobbs C. L., 2008, *MNRAS*, 391, 844
- Donovan Meyer J. et al., 2012, *ApJ*, 744, 42
- Duric, N., Gordon S. M., Goss W. M., Viallefond F., Lacey C., 1995, *ApJ*, 445, 173
- Engelbracht C.W., Rieke M. J., Rieke G. H., Latter W. B., 1996, *ApJ*, 467, 227
- Epinat B. et al., 2008, *MNRAS*, 388, 500
- Fixsen D. J., Bennett C. L., Mather J. C., 1999, *ApJ*, 526, 207
- Flower, D. R., & Launay, J. M. 1985, *MNRAS*, 214, 271
- Fridriksson J. K., Homan J., Lewin W. H. G., Kong A. K. H., Pooley D., 2008, *ApJS*, 177, 465
- Green S., & Thaddeus P., 1976, *ApJ*, 205, 766
- Green D. A., 2012, *AIPC*, 1505, 5
- Goldreich P., Kwan J., 1974, *ApJ*, 189, 441
- Goldsmith Paul F., Langer William D., 1999, *ApJ*, 517, 209
- Habart E. et al., 2010, *A&A*, 518, 116
- Henkel C., & Mauersberger R., 1993, *A&A*, 274, 730
- Ishizuki S., Kawabe R., Ishiguro M., Okumura S. K., Morita K. I., Chikada Y., Kasuga T., Doi M., 1990, *ApJ*, 355, 436
- Israel F. P., & Baas F., 2001, *A&A*, 371, 433
- Jansen D.J., 1995, PhD Thesis, Leiden University
- Karachentsev I. D., Kajsins S. S., Tsvetanov Z., Ford H., 2005, *A&A*, 434, 935
- Kaviraj S., Rey S. C., Rich R. M., Yoon S. J., Yi S. K., 2007, *MNRAS*, 381, 74
- Kennicutt et al., 2003, *PASP*, 115, 928
- Kirk H., 2011, *JRASC*, 105, 2
- Knapen J. H., Stedman S., Bramich D. M., Folkes S. L., Bradley, T. R., 2004, *A&A*, 426, 1135
- Koda J. et al., 2012, *ApJ*, 761, 41
- Lacey C. K., Duric N., 2001, *ApJ*, 560, 719
- Leroy A. K. et al., 2009, *AJ*, 137, 4670
- Levine E. S., Helfer T. T., Meijerink R., Blitz L., 2008, *ApJ*, 673, 183
- Matonick D. M., Fesen R. A., 1997, *ApJS*, 112, 49
- Mac Low M., McCray R., 1988, *ApJ*, 324, 776
- Martín S., Mauersberger R., Martín-Pintado J., Henkel C., García-Burillo S., 2006, *ApJS*, 164, 450
- McCray R., Kafatos M., 1987, *ApJ*, 317, 190
- Meijerink R., Spaans M., Loenen A. F., van der Werf P. P., 2011, *A&A*, 525, 119
- Murphy E. J. et al., 2010, *ApJ*, 709, 108
- Murphy E. J. et al., 2011, *ApJ*, 737, 67
- Nieten Ch., Dumke M., Beck R., Wielebinski R., 1999, *A&A*, 347, 5
- Oka T., Nagai M., Kamegai K., Tanaka K., Kuboi N., 2007, *PASJ*, 59, 15
- Penzias A. A., Jefferts K. B., Wilson R. W., 1970, *AJ*, 165, 229
- Rebolledo D., Wong T., Leroy A., Koda J., Meyer D. J., 2012, *ApJ*, 757, 155
- Regan M.W., Vogel S.N., 1995, *ApJ*, 452, 21
- Röllig M. et al., 2007, *A&A*, 467, 187
- Sandstrom K. M. et al., 2012, arXiv1212.1208S
- Sauty S., Gerin M., Casoli F., 1998, *A&A*, 339, 19
- Schinke R., Engel V., Buck U., Meyer H., Diercksen G. H. F., 1985, *ApJ*, 299, 939
- Schlegel E. M., 1994, *AJ*, 108, 1893
- Schoier F. L., van der Tak F. F. S., van Dishoeck E. F., Black J. H., 2005, *A&A*, 432, 369
- Skrutskie M. F. et al., 2006, *AJ*, 131, 1163
- Solomon P., Jefferts K. B., Penzias A. A., Wilson R. W., 1971, *AJ*, 163, L53
- Tacconi L. J., and Young J. S., 1989, *ApJS*, 71, 455
- Tenorio-Tagle G., Bodenheimer P., 1988, *ARA&A*, 26, 145
- Tomisaka K., Ikeuchi S., 1986, *PASJ*, 38, 697
- Tully, R. B., 1988, *Science*, 242, 310
- Yang B., Stancil P. C., Balakrishnan N., Forrey R. C., 2010, *ApJ*, 718, 1062
- van der Tak F. F. S., Black J. H., Schoier F. L., Jansen D. J., van Dishoeck E. F., 2007, *A&A*, 468, 627
- van der Kruit P. C., Allen R. J., Rots A. H., 1977, *A&A*, 55, 421
- Wall W. F., Jae D. T., Bash F. N., et al., 1993, *ApJ*, 414, 98
- Walsh W., Beck R., Thuma G., Weiss A., Wielebinski R., Dumke M., 2002, *A&A*, 388, 7
- Weliachew L., Casoli F., Combes F., 1988, *A&A*, 199, 29
- Weiss A., Downes D., Walter F., Henkel C., 2007, *ASPC*, 375, 25
- Weiß A., Walter F., Scoville N. Z., 2005, *A&A*, 438, 533
- Wilson R. W., Jefferts K. B., Penzias A. A., 1970, *AJ*, 161, L43

APPENDIX A: CSO OBSERVATIONS**APPENDIX B: INTEGRATED SPECTRA OF THE 8 REGIONS STUDIED**

Table A1. CSO detections.

Transition	Offset (arcsec)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	FWHM (km s ⁻¹)	Transition	Offset (arcsec)	$\int T_{\text{mb}} dv$ (K km s ⁻¹)	FWHM (km s ⁻¹)	
CI(³ P ₁ - ³ P ₀)	(0, 0)	29.9 ± 2.8	148.5 ± 15.2	CO(2-1)	(-90, -30)	7.9 ± 1.5	29.8 ± 5.4	
	(20, 0)	25.1 ± 2.9	87.3 ± 11.9		(-90, -60)	7.9 ± 1.8	25.4 ± 8.6	
	(40, 0)	5.6 ± 2.3	37.9 ± 27.3		(-120, 0)	2.5 ± 0.9	14.4 ± 5.3	
	(80, 0)	18.9 ± 2.5	155.8 ± 22.6		(-120, 120)	6.5 ± 1.3	25.1 ± 6.4	
	(100, 0)	4.1 ± 1.3	93.3 ± 38.2		(-120, -30)	8.6 ± 1.4	30.3 ± 5.3	
	(110, 100)	4.4 ± 0.9	29.9 ± 5.7		(-120, -60)	10.8 ± 2.6	46.6 ± 17.0	
	(120, 0)	4.0 ± 1.3	41.7 ± 18.7		(-150, 30)	3.2 ± 0.8	12.1 ± 5.5	
	(150, -20)	3.8 ± 0.9	20.2 ± 4.7		(-150, 60)	3.9 ± 1.5	18.6 ± 14.1	
	CO(2-1)	(0, 0)	102.7 ± 3.0		155.5 ± 4.8	(-150, 90)	6.0 ± 1.6	41.6 ± 12.7
		(0, 30)	43.7 ± 2.4		106.6 ± 6.3	(-150, 120)	11.1 ± 2.6	73.8 ± 26.2
(0, 60)		20.3 ± 2.7	88.9 ± 14.3	(-150, -30)	5.7 ± 1.5	30.6 ± 8.5		
(0, 90)		6.6 ± 1.9	49.5 ± 17.2	(-150, -60)	8.9 ± 2.0	57.8 ± 17.8		
(0, 120)		5.5 ± 0.9	35.2 ± 7.4	(-180, -30)	4.4 ± 1.2	25.9 ± 8.1		
(0, -30)		18.4 ± 2.5	87.2 ± 12.8	(-210, 0)	3.0 ± 1.1	18.4 ± 11.1		
(0, -90)		7.0 ± 1.5	31.8 ± 9.1	(-210, 90)	6.5 ± 2.6	43.6 ± 27.7		
(0, -120)		9.4 ± 2.4	44.9 ± 15.7	(-210, 120)	16.2 ± 2.7	114.1 ± 18.8		
(30, 0)		31.7 ± 3.6	98.6 ± 17.7	(-210, 180)	13.1 ± 2.3	94.8 ± 17.5		
(30, 30)		31.4 ± 2.4	96.6 ± 9.2	(-210, -60)	8.4 ± 2.2	64.6 ± 19.3		
(30, 90)		10.9 ± 1.7	48.3 ± 11.3	(-240, 60)	3.6 ± 1.1	23.6 ± 8.2		
(30, 120)		4.6 ± 1.3	30.5 ± 10.3	(-240, 180)	11.8 ± 2.5	93.9 ± 20.4		
(30, -30)		13.2 ± 2.7	81.3 ± 18.2	(-240, 240)	34.6 ± 4.2	217.5 ± 28.2		
(30, -60)		7.9 ± 1.4	39.1 ± 7.3	CO(3-2)	(0, 0)	111.6 ± 2.5	151.0 ± 3.7	
(30, -90)		4.3 ± 1.2	29.5 ± 9.1		(0, 10)	100.8 ± 2.2	155.9 ± 3.6	
(60, 30)		15.0 ± 2.2	67.6 ± 11.9		(0, 20)	66.7 ± 5.2	138.0 ± 12.3	
(60, 60)		9.5 ± 1.7	47.7 ± 11.1		(0, -10)	89.1 ± 3.0	133.1 ± 5.3	
(60, 90)		7.9 ± 1.2	25.5 ± 4.4		(10, 0)	131.2 ± 4.2	155.0 ± 5.3	
(60, 120)		4.5 ± 1.2	24.9 ± 7.3		(10, 10)	54.9 ± 7.9	107.3 ± 26.6	
(60, -60)		3.7 ± 1.0	20.7 ± 6.5		(10, -10)	79.5 ± 5.8	169.9 ± 13.6	
(90, 0)		11.4 ± 2.5	61.4 ± 22.5		(20, 0)	29.8 ± 2.6	75.1 ± 9.7	
(90, 30)		9.2 ± 1.5	25.3 ± 6.5		(20, -20)	7.3 ± 1.9	20.1 ± 5.1	
(90, 60)		5.6 ± 1.2	22.2 ± 6.3		(40, 0)	13.0 ± 1.2	57.2 ± 9.2	
(90, 90)		12.4 ± 1.6	46.4 ± 7.8		(60, 0)	3.9 ± 1.1	20.8 ± 6.6	
(90, 120)		8.4 ± 1.3	36.8 ± 5.6		(80, 0)	3.9 ± 0.9	11.4 ± 3.7	
(90, 150)		5.1 ± 1.5	31.9 ± 11.1		(90, 100)	9.2 ± 1.7	35.9 ± 8.5	
(120, 0)		4.7 ± 1.3	24.0 ± 6.9		(100, 0)	2.0 ± 0.6	14.3 ± 3.7	
(120, 30)		7.8 ± 1.4	25.4 ± 4.9		(100, 90)	7.0 ± 1.4	25.0 ± 5.2	
(120, 60)		6.5 ± 1.1	22.4 ± 3.9		(100, 110)	6.7 ± 1.3	14.7 ± 3.6	
(120, 90)		9.1 ± 1.6	52.4 ± 10.7		(110, 100)	11.2 ± 0.7	34.1 ± 2.4	
(120, -120)		6.6 ± 2.2	42.5 ± 21.8		(110, 110)	3.4 ± 0.9	16.5 ± 4.5	
(150, 0)		8.7 ± 1.2	29.8 ± 5.1		(120, 90)	2.8 ± 0.9	8.4 ± 3.4	
(150, 60)		9.3 ± 2.1	43.4 ± 15.0		(140, -20)	8.8 ± 0.8	25.2 ± 2.3	
(150, 90)		8.4 ± 1.8	43.0 ± 12.9		(150, 0)	6.1 ± 0.6	27.9 ± 3.1	
(150, -30)		9.7 ± 1.6	25.2 ± 4.1		(150, -10)	6.6 ± 0.6	22.1 ± 2.4	
(150, -60)		3.4 ± 1.1	23.4 ± 7.9		(150, -20)	10.8 ± 1.5	26.8 ± 4.3	
(180, 0)		7.7 ± 1.5	38.8 ± 9.2		(150, -30)	6.2 ± 0.7	21.1 ± 2.5	
(180, 30)		5.6 ± 1.5	28.8 ± 9.3	(150, -40)	3.7 ± 0.6	14.4 ± 2.4		
(180, 60)		7.7 ± 2.4	44.7 ± 17.6	(160, -20)	9.2 ± 1.6	23.5 ± 4.7		
(180, -30)		7.3 ± 1.9	32.5 ± 8.9	(-10, 0)	70.3 ± 2.9	129.8 ± 6.2		
(210, 30)		5.9 ± 1.4	34.9 ± 9.8	(-10, 10)	37.9 ± 2.9	125.9 ± 11.0		
(240, -30)		9.4 ± 2.3	76.8 ± 22.9	(-10, -10)	36.9 ± 3.7	116.0 ± 15.9		
(-30, 0)	13.1 ± 2.7	97.7 ± 26.2	(-20, 0)	8.9 ± 2.7	14.2 ± 6.0			
(-30, 30)	25.1 ± 2.9	170.1 ± 21.6	(-20, 20)	3.0 ± 1.7	14.5 ± 6.2			
(-30, 90)	12.1 ± 1.9	86.2 ± 14.1	(-40, 0)	5.0 ± 0.4	36.1 ± 3.5			
(-30, -60)	11.7 ± 2.2	54.1 ± 13.3	CO(4-3)	(0, 0)	187.1 ± 5.5	144.9 ± 4.6		
(-30, -90)	8.6 ± 1.4	31.6 ± 5.9		(0, 10)	40.0 ± 7.9	105.2 ± 21.7		
(-30, -120)	9.1 ± 2.1	68.3 ± 21.2		(10, 0)	167.4 ± 9.9	137.4 ± 8.8		
(-60, 0)	11.4 ± 1.8	39.5 ± 8.6		(20, 0)	41.9 ± 3.6	141.3 ± 13.0		
(-60, 60)	10.2 ± 1.7	46.9 ± 9.5		(110, 100)	9.4 ± 1.3	27.1 ± 3.9		
(-60, -30)	9.5 ± 1.4	33.2 ± 4.7		(150, -20)	13.4 ± 1.9	27.5 ± 5.1		
(-60, -60)	7.3 ± 1.6	30.2 ± 9.9	(-110, -30)	6.5 ± 1.1	19.0 ± 4.6			
(-60, -150)	7.1 ± 1.9	56.4 ± 19.0	CO(6-5)	(0, 0)	70.1 ± 10.4	101.1 ± 18.5		
(-90, 60)	5.6 ± 1.5	31.3 ± 9.2		(5, 0)	90.7 ± 9.8	129.5 ± 13.9		
(-90, 90)	4.3 ± 1.3	30.0 ± 8.1		(10, 0)	152.4 ± 23.7	191.3 ± 30.8		
(-90, 120)	19.2 ± 3.8	136.0 ± 37.0		(150, -20)	13.9 ± 4.8	20.2 ± 8.3		
(-90, 0)	3.3 ± 1.0	12.1 ± 3.3						

Notes: Offsets are measured with respect to the galaxy centre.
© 2012 RAS, MNRAS 000, 1–18

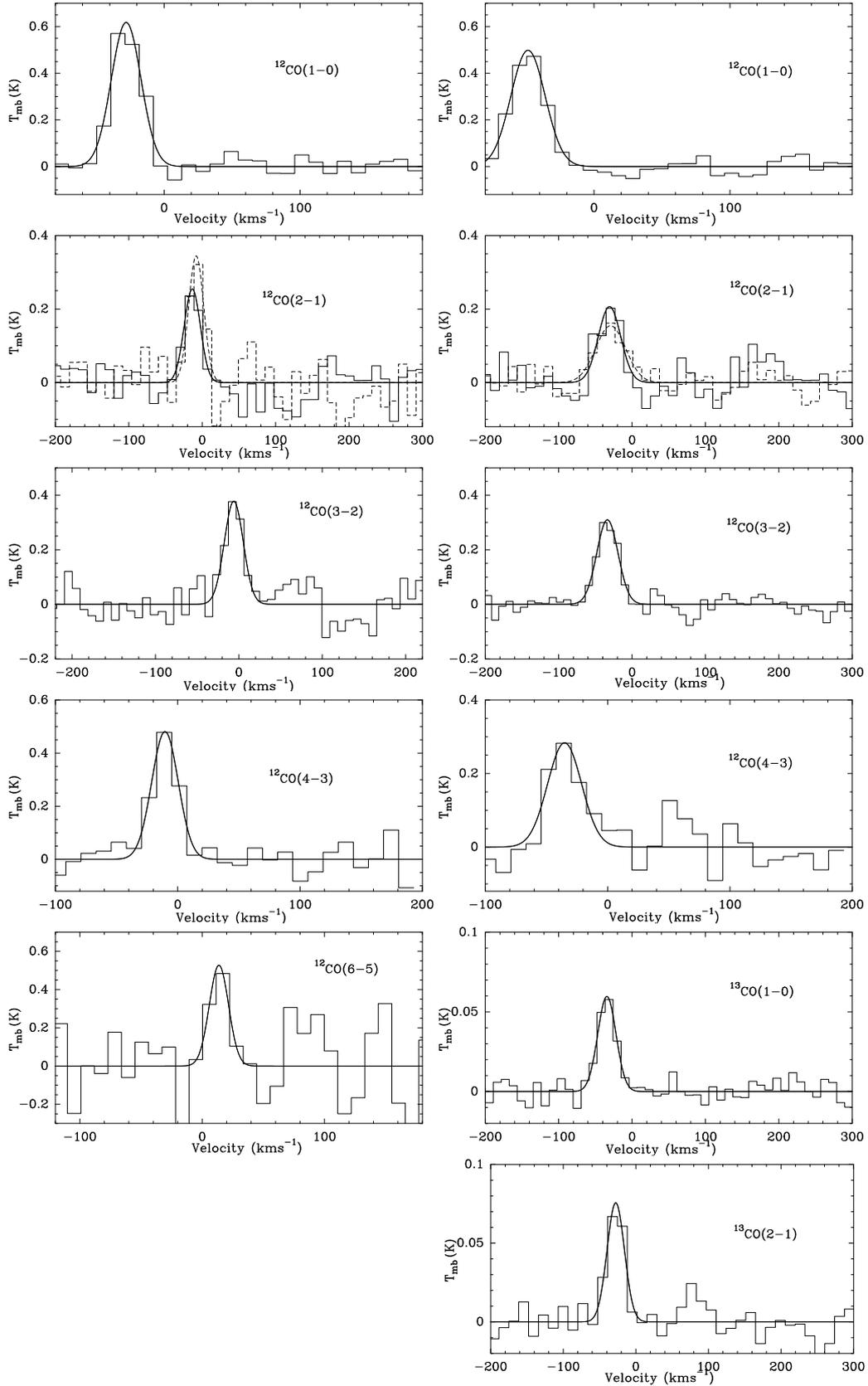


Figure B1. Integrated spectra used in the line ratio analysis for region 1 (left) and 2 (right). Gaussian fits are overlaid. The $^{12}\text{CO}(2-1)$ line integrated intensity and line width in each region was obtained by interpolating those of the two closest detections of the large-scale mapping. These are shown as dashed and solid lines in the $^{12}\text{CO}(2-1)$ panel.

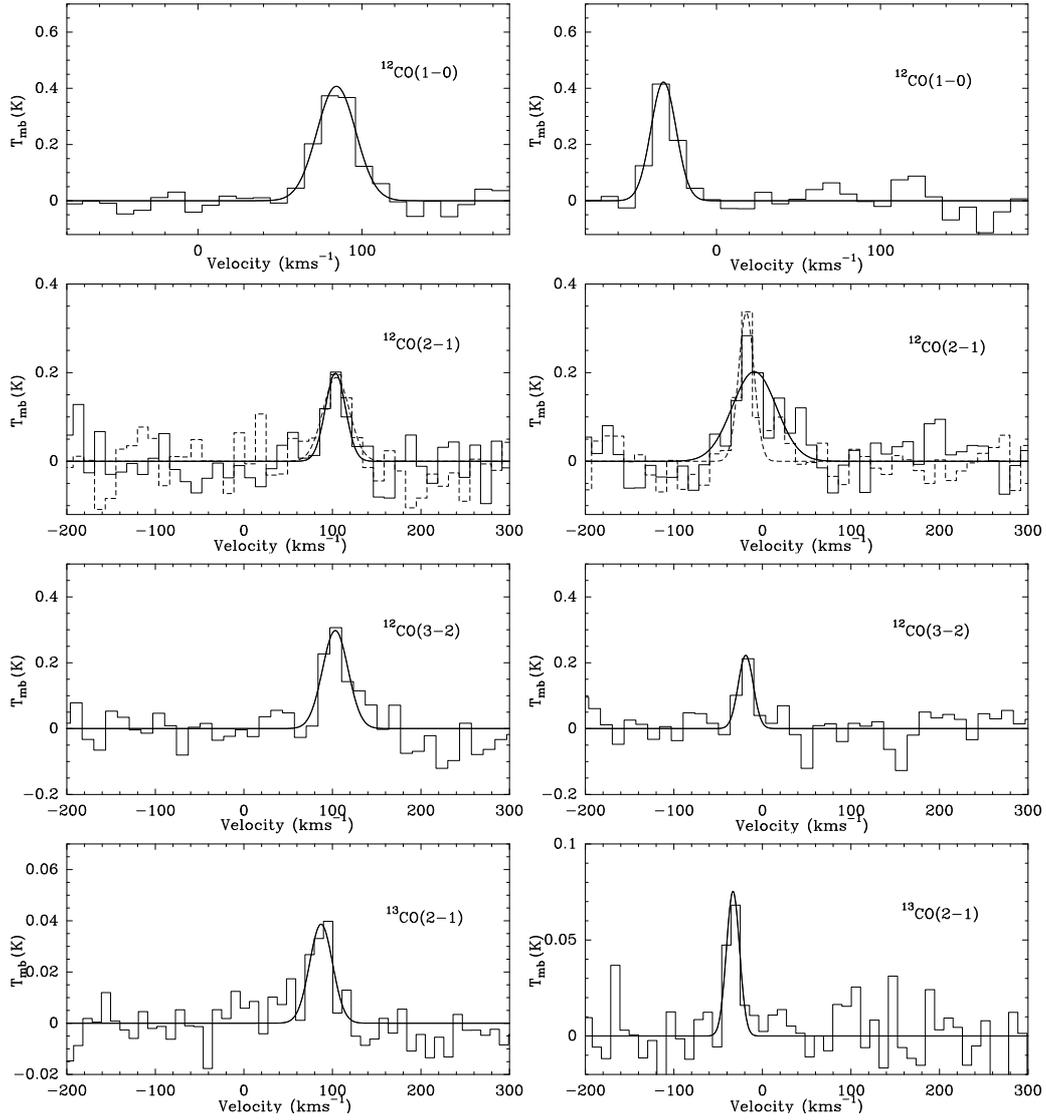


Figure B1. (Continued.) Region 3 (left) and 4 (right).

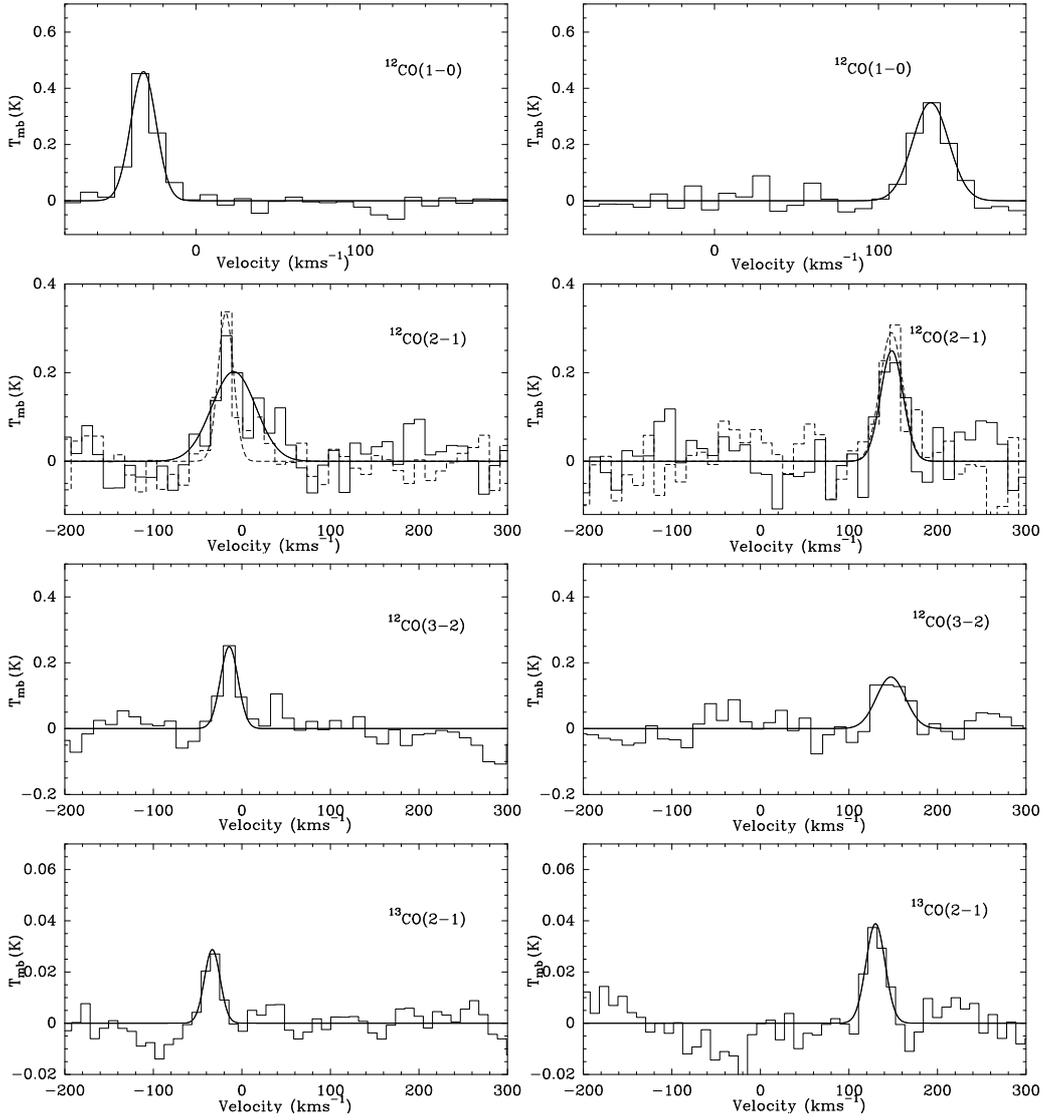


Figure B1. (Continued.) Region 5 (left) and 6 (right).

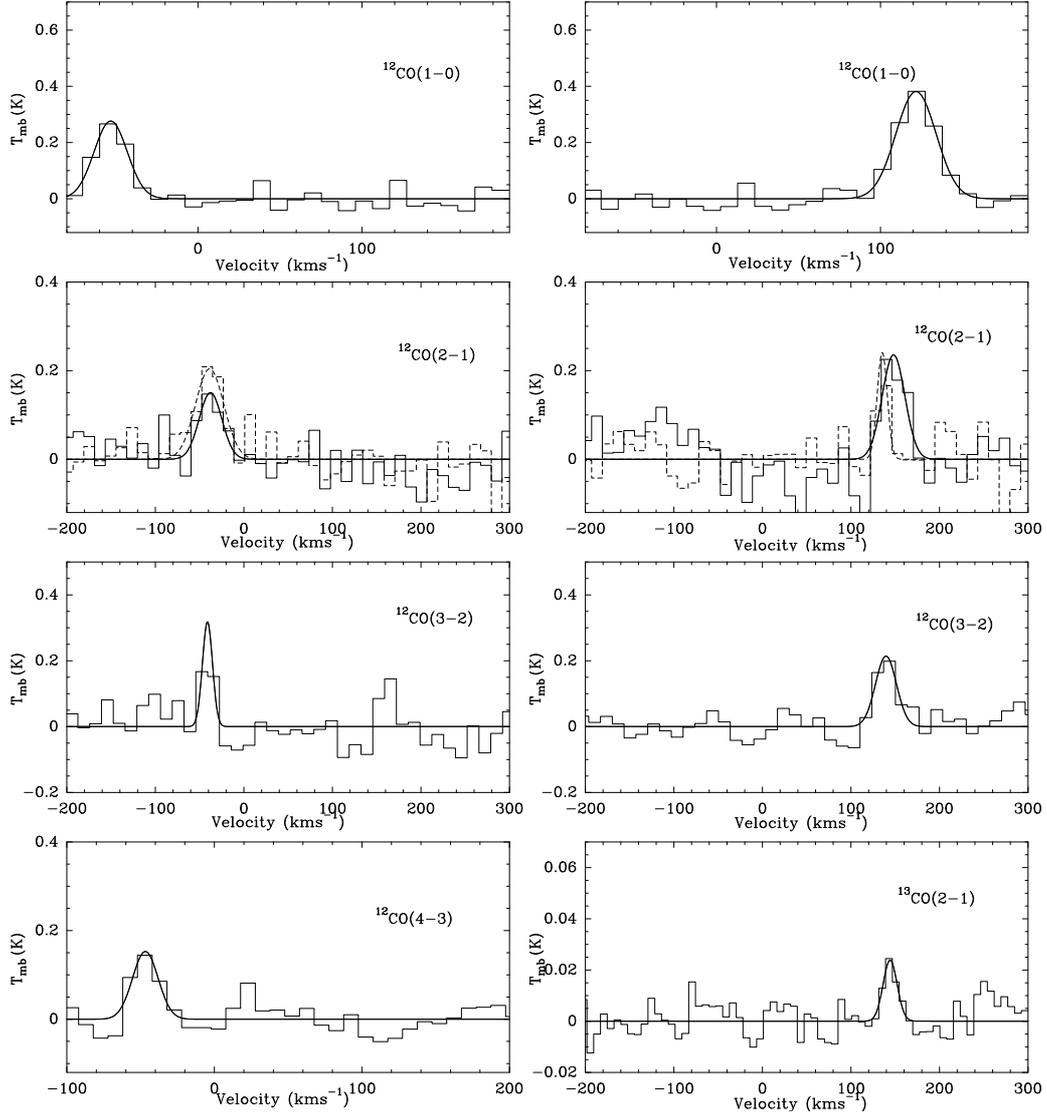


Figure B1. (Continued.) Region 7 (left) and 8 (right).