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Molecular line CO (2→1) observations of ultraluminous IRAS galaxies

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Abstract. CO (J = 2→1) observations of six ultraluminous IRAS galaxies are presented. Four of these galaxies have no previous CO J = 2→1 data and two have no previous CO detections at all. Based on these observations, molecular hydrogen masses are estimated and range from 5×10^9 to 1.8×10^{10} $M_\odot$. The present data follow the well established correlation that exists between the infrared luminosity L_{IR} and the molecular mass content. The high values of the L_{IR}/M_{H_2} suggest either an increased star formation efficiency and / or an additional source of luminosity such as an active nucleus. The ratio R = (J = 2→1) / (J = 1→0) between the J = 2→1 and 1→0 line temperatures, is examined next using our J = 2→1 intensities and other published CO J = 1→0 data. For Arp 220, Mrk 231, Mrk 273 R lies in the range 0.7 to 1.1; for IRAS 05189 the CO intensity and the ratio R were both found to have extremely low values. The low values of R≤1 found for all galaxies, suggest that the line profiles are dominated by emission coming from optically thick thermalized CO. Finally the line profiles are examined and compared to published models concerning the distribution and kinematics of the gas. Assuming that the CO is distributed in a disk as in normal spiral galaxies, then this region is probably concentrated towards the center of the galaxies.

Key words: galaxies: ISM – galaxies: active – radio lines: galaxies

1. Introduction

One of the many exciting results of the IRAS satellite was the discovery of a large population of galaxies that are powerful far-IR emitters. These "Ultraluminous IRAS Galaxies" (ULGs) have luminosities comparable to those of quasars i.e. $L_{FIR} > 10^{12}$ $L_\odot$. Compared at the same far-IR luminosity, such objects are ~ 100 times as common as quasars. Even compared at the same bolometric luminosity (Soifer et al. 1986) such objects are as common as quasars (Lawrence et al. 1986) if not more so. They are therefore a significant new component of the extragalactic world. In active galaxies the interstellar material is closely related to the physical processes of the activity itself, either through star formation or through the inflow of gas onto a massive relativistic object. Therefore the study of the interstellar matter in these sources via molecular lines or using its dust emission, is of great interest.

Sanders et al. (1991) presented an extensive survey of the CO (1 → 0) emission from high luminosity infrared galaxies with infrared luminosities, L_{IR}(8-1000 μm) > 2 × 10^{10} $L_\odot$. Chini et al. (1992) and Krugel et al. (1990) observed the CO (2 → 1) and CO (1 → 0) emission for Markarian galaxies, and Garay et al.(1993) detected CO (2 → 1) and ^{13}CO(1 → 0) emission from a sample of luminous southern infrared galaxies.

However the properties of the most luminous galaxies (L>10^{12} $L_\odot$) are of particular interest. For galaxies with L ~ 10^{11} $L_\odot$ it is fairly well accepted that they are powered by starbursts. For galaxies with L ~ 10^{12} $L_\odot$ it is still unclear whether the energy source is a burst of star formation or a hidden quasar.

In this paper CO (2 → 1) observations for six ultraluminous galaxies are presented. The CO observations are used to compute total masses of molecular gas and together with the infrared luminosities L_{IR} the ratio L_{IR} / M_{H_2} is estimated. The ratio of the integrated CO line emission, R = (J = 2→ 1) / (J = 1→ 0), which gives information about the excitation temperature of the molecular gas and the conditions of the gas emitting region, is examined next. This ratio is estimated for four of the sample galaxies (those galaxies for which CO (1 → 0) observations exist). The accuracy of the present measurements and the values of R found for the sample galaxies are discussed and compared to other published results. The galaxies observed were selected according to the following criteria: i) Declination > -40, ii) 60μm

Send offprint requests to: D. Rigopoulou flux density > 2 Jy, iii) Luminosity $L_{FIR} > 10^{12} L_\odot$ (assuming H_0= 50 km s^{-1} Mpc^{-1} and $\Omega = 1$) and iv) redshift $z < 0.05$.

2. Observations and data analysis

2.1. Observations

The CO data were collected on the nights of 16 and 17 March 1993 using the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii [1]. For the observations a single-channel SIS receiver(Receiver A2) was used together with the AOS backend spectrometer. The SSB noise temperature was 150 K, and the total system temperature was 325 K at 230 GHz (Matthews 1992). The AOS backend spectrometer had a total bandwidth of 500 MHz equivalent to 625 km/sec at the observing frequency. The telescope beamsize was 23 arcsec, and the tracking was estimated to be accurate to $\pm 4''$ (rms). Chopping was done in azimuth with a throw of $60''$ and a frequency of 1 Hz employing a double beam switching technique. Spectra were obtained with the velocity centered on the known optical redshifts.

The data are presented on a scale of main beam temperature T_{mb} which is appropriate if the source sizes are of the same order as the beam sizes. The main beam efficiency η_{mb} for the JCMT, is equal to 0.63. To compare observations of both transitions J = 1→0 and J = 2→1 done with different telescopes and different beam sizes, temperatures must be expressed in a "beam-independent" way. Therefore we use brightness temperatures T_{br} where $T_{br} = T_{mb}/\eta_c$ (Ulich and Haas 1976), where η_c is the source's brightness distribution (the temperature T The source sizes and the actual values of η_c used to calculate T_{br} are given in Sect. 4.

2.2. Line spectra and intensities

Fig. 1 presents the CO J= 2→1 spectra for all the objects.

The redshift range for these galaxies lies between 0.054 and 0.018 which is equivalent to velocities of 5000 and 13000 km s^{-1}, and the peak intensities detected were between 7 and 143 mK. The extremely broad profile of Arp 220 is similar to obsevations of the same transition by Solomon et al. (1990). Sanders et al. (1991) observed the CO J = 1→0 transition line from Arp 220 and report a FWHM of ~ 400 km sec^{-1}.

Table 1 summarizes the observational parameters for the individual sources.

In column (1) the IRAS (or other) name of the galaxies is presented, in column (2) and (3) positions which correspond mainly to radio positions for the nucleus from Condon et al. (1991) and references therein, in column (4) optical redshifts from QIGC (QMW Infrared Galaxy Catalogue) (Rowan-Robinson et al. 1991) and references therein, and in column (5) total on source integration times in seconds. Table 2 summarizes the CO line parameters for the observed galaxies.

Table 1. Observational parameters

IRAS NAME other	R.A. (1950)	Decl. (1950)	redshift (optical)	Int. time (sec)
05189-2524	05 18 58.6	-25 24 39	0.0426	4500
09320+6134 (UGC05101)	09 32 04.7	+61 34 37	0.0400	4500
12540+5708 (Mrk 231)	12 54 07.4	+57 08 39	0.0418	4500
13428+5608 (Mrk 273)	13 42 51.6	+56 08 14	0.0373	4200
15327+2340 (Arp220)	15 32 46.3	+23 40 10	0.0183	2700
1720-0014	17 20 48.2	-00 14 17	0.0425	3600

In column (1) the source name is listed, in column (2) the total CO intensity I_{CO} obtained by integrating T_{mb} over the full velocity range, in column (3) the peak T_{mb} temperature, in columns (4) and (5) comparison between the optical velocities (expected from the optical redshifts according to which the scans were centered) and centroid velocities from the CO emission are given and finally in column (6) the CO line widths at FWHM. The CO line widths were estimated by fitting a single gaussian to the data. For 05189+2524 the 2 σ upper limit is given as this was found to be a weak CO J = 2→1 source despite its relatively strong CO J= 1→0 emission. We do not believe this discrepancy is due to mispointing or a receiver problem.

3. Molecular masses and luminosities

3.1. CO luminosities

The CO luminosity is defined as the integrated line intensity multiplied by the surface area which the beam at the distance of the source covers on the sky. Therefore:

$$L_{CO} = I_{CO} A_s \qquad (1)$$

where

$$A_s = \pi (d_B/2)^2 \qquad (2)$$

where d_B (pc) is the half-power beam diameter in pc at the source distance. Finally the CO luminosity becomes:

$$L_{CO} = \frac{\pi I_{CO} d_B^2}{4} \; (K\, km\, sec^{-1}\, pc^2) \qquad (3)$$

Table 3 shows the values of the CO luminosities. Distances for each object were calculated assuming H_0= 50 km s^{-1} Mpc^{-1}.

[1] The James Clerk Maxwell Telescope is operated by the Royal Observatory, Edinburgh (ROE) on behalf of the United Kingdom Particle Physics and Astrophysics Research Council (PPARC), the Netherlands Organisation for the Advancement of Pure Research (ZWO), the Canadian National Research Council (NRC), and the University of Hawaii (UH).

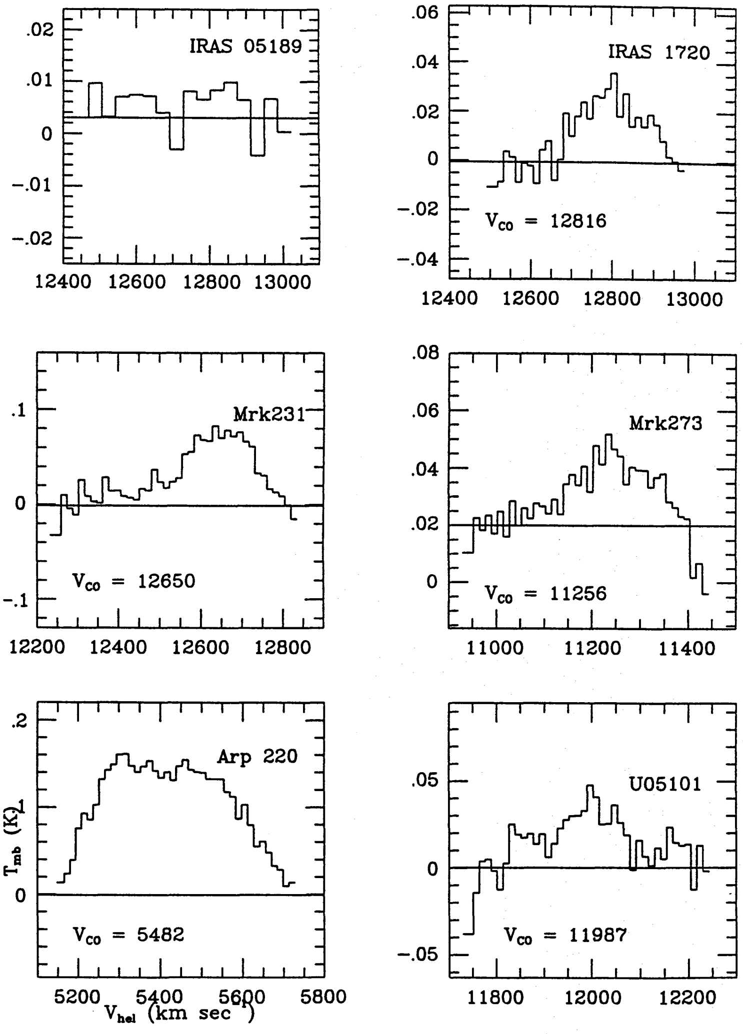

Fig. 1. Line profiles of the CO (2→1) emission from six ultraluminous IRAS galaxies. Most spectra have been smoothed to a velocity resolution of 20 km s^{-1}. The intensity scale is in units of T_{mb}. The x-axis is heliocentric velocity v_{hel} expressed in km s^{-1}

Table 2. Line emission parameters

IRAS NAME other	Ico* (K km/sec)	Tpeak* (mK)	V_{opt} km/sec	V_{CO} km/sec	ΔV(FWHM) km/sec
05189-2524	<1.9**	<7.9	12771	–	–
09320+6134 (UGC05101)	5.0±1.6	27.8	11991	11987	300
12540+5708 (Mrk 231)	7.2±1.4	60.25	12531	12650	200
13428+5608 (Mrk 273)	5.1±1.3	42.75	11182	11256	280
15327+2340 (Arp220)	38.7±4.8	143.2	5486	5482	450
1720-0014	3.4±1.1	21.99	12741	12816	260

* both on "Tmb" scale.
** 2 σ upper limit.
Typical rms noise 5-7 mK.

Table 3. Total molecular hydrogen masses CO and IR luminosities

IRAS NAME other	D (Mpc)	$\log L_{CO}$ (K km $s^{-1}pc^2$)	$\log M(H_2)$ ($M_\odot$) (optically thin limit)	$\log M(H_2)$ ($M_\odot$) (empirical)	$\log L_{IR}$ $L_\odot$	$\log(L_{IR}/M(H_2))$ ($L_\odot M_\odot^{-1}$)
05189-2524	255	9.00	>8.92	9.68	12.06	2.38
09320+6134 (UGC05101)	240	9.37	>9.28	10.05	12.13	2.08
12540+5708 (Mrk 231)	250	9.56	>9.47	10.24	12.66	2.42
13428+5608 (Mrk 273)	224	9.32	>9.22	10.00	12.29	2.29
15327+2340 (Arp220)	109	9.57	>9.48	10.25	12.32	2.07
1720-0014	255	9.25	>9.17	9.93	12.54	2.61

3.2. Mass of molecular gas: empirical method

The determination of molecular hydrogen masses from the CO observations is based on a relationship which assumes that H_2 column density is proportional to the velocity integrated CO emission:

$$N_{H_2} = X \int T_R^*(CO)dV \qquad (4)$$

where X is a constant (Israel 1988).

Several methods have been used to empirically determine the conversion factor X for molecular clouds within our own Galaxy (Scoville et al. 1986, Young and Scoville 1982, Bloemen et al. 1986). All these methods essentially agree to first order, and we adopt:
$N(H_2)$/mol cm^{-2} = 3× $10^{20}(I_{CO}$/K km s^{-1}). Using the above conversion factor the mass of H_2 is given by

$$M(H_2)[M_\odot] = 4.78 L_{CO}[K\ km\ s^{-1}\ pc^2] \qquad (5)$$

where L_{CO} is the CO luminosity measured in K km s^{-1} pc^2. Table 3 gives mass estimates based on Eq. (2).

As mentioned earlier the above conversion factor comes from Galactic observations therefore it is not clear whether the above relationship will hold in other galaxies. Dickman et al. (1986), Maloney and Black (1988) and Maloney (1990) show that the theoretically expected conversion factor depends on the mean density of the gas, the CO excitation temperature and the CO abundance.

3.3. Mass of molecular gas: optically thin method

A lower limit on molecular hydrogen masses can be obtained by assuming that the emission is optically thin. The CO J = 2→1 column density can then be estimated from the integrated intensity,assuming that the levels are populated in LTE at an excitation temperature T_{ex}:

$$N(CO) = \frac{2.32 \times 10^{15} \left[\frac{I_{CO}}{K\ km\ sec^{-1}}\right](1 + 8 \times 10^{-3}/T_{ex})}{(1 - \exp(-11.06/T_{ex}))\exp(-11.06/T_{ex})} cm^{-2} \qquad (6)$$

We have adopted an excitation temperature T_{ex}=20 K, a value taken from a theoretical study of the conversion factor from CO to M_{gas} by Chini, Krugel and Steppe (1992). Note that N(CO) is only weakly dependent on T_{ex}, depending mostly on the integrated intensity of the CO.

Equation (4) gives a beam averaged CO column density. The mass of the gas can then be derived from the CO column densities by assuming the CO/H_2 abundance ratio, which we take to be $[CO]/[H_2] \sim 10^{-4}$, but of course this number may be uncertain by a factor of several. These mass estimates represent an absolute lower limit to the total number of H_2 molecules and the real hydrogen mass. This is due to the assumption that emission comes from optically thin gas, and therefore that the flux detected is proportional to the number of H_2 molecules, consequently giving a lower limit of the total number of H_2 molecules. Table 3 gives gas mass estimates using Eq. (6). These are all substantially smaller than the mass estimates of Sect. 3.2 strongly suggesting that CO is optically thick.

3.4. The IR luminosity – molecular mass relationship

The relationship between IR luminosity and molecular masses has already been the subject of extensive study by several workers (Sanders et al. 1991, Mazzarella et al. 1993), using mass estimates based on CO (1→0) observations. Here we confirm that the present CO (2→1) data follow the well established relationship between molecular mass content and infrared luminosities.

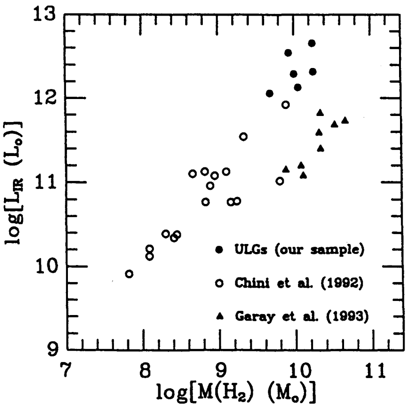

Fig. 2. The infrared luminosity is shown as a function of M(H_2)=(4.78 L_{CO}). The six ultraluminous galaxies observed are plotted as large solid circles. CO (2 → 1) data for a sample of Markarian Galaxies (Chini et al. 1992) are plotted as open circles while data for eight luminous southern Galaxies (Garay et al. 1993) are plotted as solid triangles

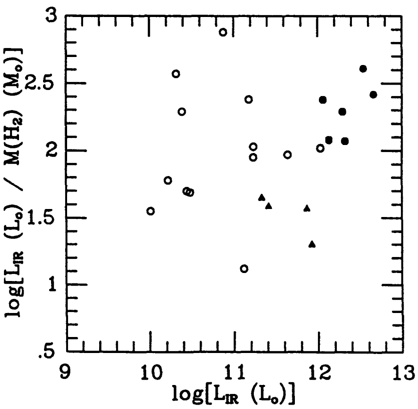

Fig. 3. The infrared luminosity-to-H_2 mass ratio L_{IR}/M(H_2), is shown as a function of the infrared luminosity L_{IR}

In Fig. 2, the infrared luminosities are plotted versus the total H_2 mass for the sample of the ULGs, along with a sample of Markarian galaxies from Chini et al. (1992), and eight luminous ($L_{IR} > 10^{11} L_\odot$) southern galaxies from Garay et al. (1993).

A strong correlation is seen between the infrared luminosities and the H_2 masses, indicating a connection between the amount of material in the interstellar medium content and the infrared luminosity. Clearly the ULGs occupy the upper right-hand part of the plot while the southern luminous galaxies, although having similar masses to the ULGs, lie below them with the Markarian galaxies.

Fig. 3 shows the ratio of the infrared luminosity to molecular gas mass, L_{IR} / M_{H_2}, versus infrared luminosity L_{IR}, for the ULGs, the Markarian galaxies and the southern luminous galaxies.

The IR luminosity to H_2 ratio has values in the range 10 – 160. These values are higher than average ratios found in spirals or classical starbursts (Mirabel 1990), or in active galactic molecular clouds with HII regions (Mooney and Solomon

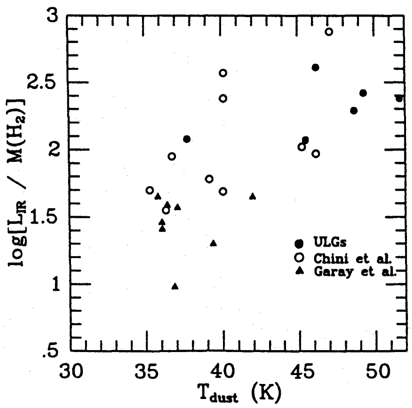

Fig. 4. The infrared luminosity-to-H_2 mass ratio L_{IR}/M(H_2), is shown as a function of the dust temperature T_d

1988). For the ULGs the ratio L_{IR} / M_{H_2} has values > 100, thus they have some of the highest values compared to the other galaxies. It is likely therefore that these high luminosity galaxies may have an additional source of energy such as intense star formation events and/or an active nucleus.

Our results seem to be in good agreement with those found by Sanders et al (1991) who examined the relationship between infrared luminosities and molecular gas mass for a sample of ULGs based on the CO (1 → 0) observations. However it should be noted that the Garay et al. (1993) values seem strange. For a given luminosity their mass estimates are extremely high. Three possibilities exist for this: (a) this could be due to possible overestimates of the masses, (b) it could be true indeed, and then the correlation between molecular masses and luminosities is not a linear one, but it is a wedge. If the latter is true then the strong correlation seen in the Sanders et al. (1991) results, holds only in the upper envelope of the wedge and corresponds to galaxies which show a maximum efficiency in star formation. Finally, (c) it could be due to differences in the dust temperatures of the galaxies in the Garay (1993) sample. Indeed, an inspection of the values of the dust temperatures of these galaxies shows that they are lower than the dust temperatures of the galaxies of the ULG and the Markarian samples. This is more clearly shown in Fig. 4 where the L_{IR}/M_{H_2} ratio is plotted as a function of the dust temperature, T_{dust}. Dust temperatures were derived from the ratio 60/100 μm flux densities and assuming a λ^{-1} emissivity law. From Fig. 4 it is evident that as L_{IR}/M_{H_2} increases, so does the temperature. In most cases the additional source of energy mentioned above, is starburst events, therefore the molecular gas is used for star formation rather than fueling an active nucleus, as it will be discussed later when the line profiles will be examined.

4. The ratio R = (J = 2→1) / (J = 1→0)

The ratio R is defined as the ratio of the velocity integrated brightness temperature of the J = 1→0 and J = 2→1 lines. Since the observations of the CO(2 → 1) and CO (1 → 0) transitions were performed with different beams, the determination of the ratio of brightness temperatures requires knowledge of the angular size of the emitting region. The angular size of the emitting region has not been determined for all the objects of our sample. For two sources, Arp 220 and Mrk 231 there exist interferometric observations, so their real sizes have been estimated. Radford et al. (1991) determined the size of Arp 220 from CO (2–1) interferometric maps and found it to be 7.7 arcsec. For Mrk 231 Scoville et al. (1989) found that almost 100% of the emission originates from a 7 arcsec diameter region while Radford et al (1991) report this value as an upper limit only. In the present calculations the size of 7 arcsec was used. In order to compute the line ratios for the rest of the galaxies, in absence of evidence indicating the contrary, we assume that the distribution and extent of the molecular gas is similar to that measured in other members of the ULGs (Radford et al 1991). In most cases the molecular emission is generally detected at the nucleus of the galaxies. We will thus assume a source size of 10 arcsec which at a mean distance to the source of 250 Mpc the FWHM beamwidth at 230 GHz corresponds to $\sim$ 10 kpc. So if the extent of the molecular gas in the sources studied here, is not very much different than that observed for similar objects, then the whole molecular line emitting region must lie completely in the telescope beam. It was also found that the integrated brightness temperature is not very sensitive on the assumed angular size. A change of 2 arcsec in the assumed source extent causes the brightness temperature to vary by as little as 5% only as long as the source size is kept much less than the angular size of the telescope beam. For the JCMT a beam size of 23 arcsec was assumed. In all the following calculations the source size was assumed to remain constant for both the J = 2→1 and J = 1→0 transitions.

The line ratio R then is defined as:

$$R(\frac{2 \rightarrow 1}{1 \rightarrow 0}) = \frac{T_{mb,21}}{T_{mb,10}}(\frac{s^2 + b_{21}^2}{s^2 + b_{10}^2}) \qquad (7)$$

where $T_{mb,21}$ and $T_{mb,10}$ are the main beam temperatures of the CO (2–1) and the CO (1–0) transitions respectively, s is the assumed source size and b_{21} and b_{10} are the angular sizes of the CO (2–1) and the CO (1–0) observations. It should also be noted that although we might be a long way off the true brightness temperature if the source size is very different from 10 arcsec the ratio R should be fairly robust as long as the true source size is smaller than the beam size.

In Table 4 the CO (1–0) values used to estimate the R, together with any other CO (2–1) value found in the literature are presented.

So in column (1) the source name, in column (2) brightness temperatures as estimated from our observations (with a beam size of 21 arcsecs), in column (3) and (4) CO brightness temperature values for the two transitions CO (1–0) and CO (2–1) respectively, (from the literature) and in column (5) references together with the telescopes used for each observations are presented. The velocity integrated line ratios vary between 0.7 and 1.1 therefore indicating that the physical conditions differ from source to source.

The ratio R gives information about the excitation temperature and the optical thickness of the molecular gas. The theoretically expected ratio R is plotted in Fig. 5 as a function of the excitation temperature T_{ex} for the limits of optically thick and optically thin gas.

As it can be seen from the plot, for optically thin gas and high excitation temperatures the ratio R has a value around 4 while for T_{ex} = 20 K R = 2.30. For optically thick gas and high T_{ex} the ratio R has a value of 1 and for T_{ex} = 20 K, R = 0.86. However, from IR colours it is found that $T_{dust} \sim$ 50 K. If we then assume that $T_{ex} = T_{dust}$ and the gas is optically thick, as argued in Sect. 3.3, then the ratio R = 0.85, but if it is optically thin, R = 3.18. In what follows the ratios of the velocity integrated brightness temperature for four individual galaxies are discussed.

4.1. Arp220

The peculiar galaxy Arp 220 has been one of the most well-studied galaxies in CO emission. The remarkable feature of this galaxy is its large velocity spread which is found to be almost 400 km s^{-1} (Solomon et al. 1990) in both the J= 1→0 and J = 2→1 transitions. The FWHM velocity of 450 km s^{-1} in the present data agrees well with these other published values.

Solomon et al. (1990) detected CO J = 1→0 and CO J = 2→1 emission from this galaxy with the IRAM 30m telescope with 22 (CO J = 1→0) and 13 arcsec (CO J = 2→1) beams. They report T_{mb}(J = 1→0) = 0.25 mK and a T_{mb}(J = 2→1) = 0.3 mK. These values, expressed as intinsic brightness temperatures, are T_{br}(J = 1→0) = 2193 mK and T_{br}(J = 2→1) = 1154 mK. Sanders et al. (1991) also detected CO (J = 1→0) emission from Arp 220, reporting T_R^* = 26 mK, or T_{br} = 1352 mK.

The present value in the (J = 2→1) transition (1440 mK) is $\sim$20% higher than the value reported by Solomon et al (1990) with the 13 arcsec beam. The discrepancy could be attributed to differencies in the calibration and/or to different beam sizes. Using the T_{br}(J = 1→0) value estimate of Solomon et al. (1990), together with the present data, R = 0.7±0.1 (the error quoted corresponds to baseline uncertainties as well as uncertainties in the source sizes assumed). This value of R is whithin the error limits of the value of 0.6±0.1 found by Radford et al.(1991). However our value of R is higher than the value of R = 0.5 reported by Casoli et al. (1988), although these authors have have not accounted for the difference in the beam sizes of the CO(2–1) and CO (1–0) when estimating the ratio R. Our value of R becomes greater when using the T_{br} (J = 1→0) estimate from Sanders et al. (1991). In this case the ratio R becomes 1.06±0.2 but the error is larger since the baseline uncertainties in the Sanders et al. (1991) data are $\sim$ 20%.

4.2. Mrk 231

Mrk 231 is another example of a well studied galaxy. Chini et al.(1992) used the IRAM telescope with beams of 22″ and 13″ for the (J = 1→0) and the (J = 2→1) transitions respectively, detecting both transitions with a T_{mb}(J = 1→0) = 88 mK and T_{mb}(J = 2→1) = 250 mK. In terms of brightness temperature,

Table 4. Compilation of CO (1–0) and (2–1) data

IRAS NAME other	assumed source size(arcsec)	T_{br}(JCMT) mK	T_{br}(1–0) mK	T_{br}(2–1) mK	Ref.	Telescope
05189-2524	10	<43	406	–	1	(1–0)NRAO 55″
09320+6134 (UGC05101)	–	154	–	–		
12540+5708	7	710	650	1000	1	(1–0)NRAO 55″
(Mrk 231)					2	(2–1)MRT 12″
13428+5608	10	237	228	160	3	IRAM(1–0) 22″
(Mrk 273)					3	IRAM(2–1) 12″
15327+2340	7.7	1440	2193	1154	4	IRAM (1–0) 21.5″
(Arp220)					4	IRAM (2–1) 13″
1720-0014	–	122	–	–		

References:
(1) Sanders et al. (1991)
(2) Chini et al. (1992)
(3) Krugel et al. (1990)
(4) Solomon et al. (1990)

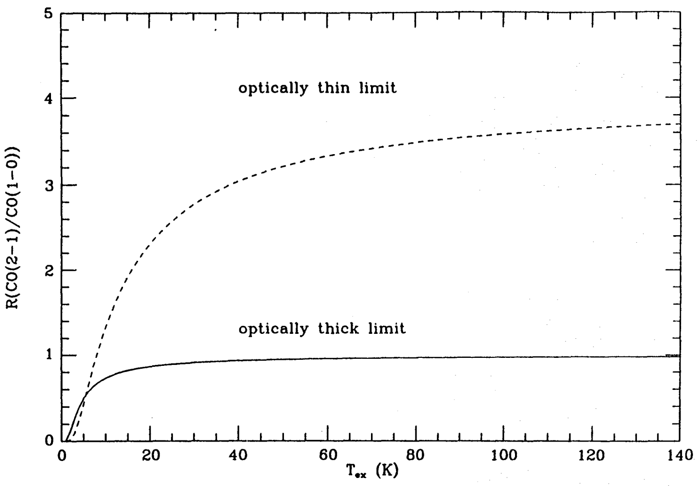

Fig. 5. The ratio R (CO(2→1/CO(1→0)) is shown as a function of the excitation temperature. The solid curve is for optically thin emission and the dashec curve is for optically thick emission

these values correspond to T_{br}(J = 1→0) = 1035 mK and T_{br}(J= 2→1) = 1000 mK. Sanders et al. (1991) detected CO(J = 1→0) emission with the 55″ beam of the NRAO 12 m telescope, quoting T_R^* = 9 mK, which corresponds to T_{br} = 650 mK. Radford et al. (1991) who obtained both spectra and maps of four infrared-luminous galaxies, including Mrk 231, report a value of T_{mb}(J = 1→0) = 97.8 mK and T_{mb}(J = 2→1) = 186 mK. If expressed in terms of brightness temperature the above values correspond to T_{br}(J = 1→ 0) = 978 mK and T_{br}(J = 2→1) = 775 mK.

Using the present observations T_R(J = 2→1) = 710 mK, which is ~ 30% lower than the value reported by Chini et al. (1992), although it is ~ 6% lower than the Radford et al. (1991) value. However the values quoted by Chini et al. (1992) for both transitions, (and especially the T_{mb} (J = 1→0) value), are high, perhaps due to callibration problems. For this reason the T_R(J = 1→0) value from was chosen Sanders at al. (1991) is used to estimate the ratio R. Correcting for the different beam sizes, R = 1.1±0.1. The ratio R becomes lower and has a value of 0.72±0.10 if the Radford et al. (1991) value for the (1–0) transition is used. The latter value of R is similar to the one estimated by Radford et al. (1991), they report a value of R = 0.7±0.1. Finally, Sanders et al. (1990) report a ratio R = 0.9 which although higher than the previous values is acceptable within their uncertainties.

4.3. Mrk 273

Mrk 273 has also been detected at both CO transitions by Krugel et al.(1990) with the IRAM 30 m telescope. For the CO(J = 1→0) line the telescope beamsize was 22 arcsec (CO J = 1→0) and 13 arcsec (CO J= 2→1) and T_{mb}(J = 1→0) = 39 mK, and T_{mb}(J = 2→1) = 47 mK. The equivalent radiation temperatures are T_{br}(J= 1→0) = 228 mK and T_{br}(J = 2→1) = 160 mK (Krugel et al. 1990). Sanders et al.(1991) report the high value of T_R^* = 13 mK which corresponds to a T_{br} = 406 mK. The present data give T_{br}(J = 2→1) = 237 mK, a value which is $\sim$ 30% higher than the (2–1) value reported by Krugel et al. (1990). To estimate R, the Krugel et al.(1990) value has been used to give R = 1.04±0.10. The value of R becomes lower R = 0.6±0.2 if the Sanders et al. (1991) CO (1–0) value is used.

4.4. IRAS 05189

For this galaxy only CO (J = 1→0) emission has previously been detected (Sanders et al. 1991) with T_R^*(J = 1→0) = 43, or T_{mb} = 406 mK (NRAO 55″). Despite the fact that IRAS 05189 is quite strong in CO (J = 1→0), it is a very weak CO(J = 2→1) source with a brightness temperature of less than 43 mK, and R $\leq$ 0.1.

The above results show that all the sources for which the ratio R was examined, were found to have a value of R $\leq$ 1. The low values of R immediately indicate that the gas is optically thick and that the particle density is low and unable to thermalise the upper level (subthermal excitation). Then in this case two possibilities exist: either all the gas has a uniform but low density distribution, unable to populate the J = 2 level in LTE, or, and this is more likely, some gas is above and some below the critical density for thermalization, and in this case the gas seen in the J = 1→0 transition is not the same as that seen in the J = 2→1. The same result, that is that the gas is subthermally excited, can be reached if one examines the excitation temperatures of the clouds. The low values of the ratio R exhibited by all sources in our sample, indicate that the excitation temperatures are low as well. Since the CO emission is believed to originate from warm molecular clouds (see i.e. Garay et al. 1993) these low excitation temperatures indicate that the gas density is too low to thermally populate the rotational levels.

Simple statistical equillibrium calculations based on the theoretical ratio of brightness temperatures (cf. Jackson et al. 1991) assuming that the gas has a kinetic temperature in the range 30-40 K imply that the molecular densities are indeed low and are in the range 120 – 340 cm^{-3}. Similar results were reached by Radford et al. (1991) for four luminous infrared galaxies (including Arp 220 and Mrk 231) and also Garay et al. (1993) for luminous southern galaxies. More accurate results on the excitation temperature and molecular gas densities can be obtained from more elaborate methods like the large velocity gradient calculations (Castets et al. 1990). Radford et al. (1991) using LVG methods found that for Arp 220 the molecular gas density falls in the range 120–700 cm^{-3} if the gas kinetic temperature varies between 10 and 80 K. At a kinetic temperature of 20 K the excitation temperature is found to be $\leq$ 14 K clearly implying subthermal excitation.

Our analysis essentially agrees to first order with other published work on the ratio R in luminous infrared galaxies. However, we should caution that since for the derivation of these ratios we have used CO (1–0) observations from different telescopes, therefore different beam sizes, baselines e.t.c., the uncertainty in the resulting value of R is bound to increase despite the relatively small uncertainties involved in our observations. There is a tendency for larger uncertainties in the values of R when CO (1–0) values from the Sanders et al. (1991) paper are used, simply because they quote a $\sim$ 20% uncertainty in their I_{CO} values due to baseline uncertainties. However, despite the uncertainties involved, all analyses indicate that the density of the molecular gas is indeed low and that the gas is subthermally excited. Moreover as it will be more clearly shown in the next section, the gas is strongly concentrated towards the central kpc regions of these galaxies.

The case of IRAS 05189 is of remarkable importance. For this galaxy an upper limit on the T_{mb} of $\sim$ 8 mK was found. The value of R was found to be $\leq$ 0.1. Such a low value of R implies that the excitation temperature is low as well (much less than 10 K), conditions are optically thick and the gas is most probably subthermally excited. As we are unable, at this stage, to give an explanation for this extremely low excitation temperature found for this object, it is necessary that more observations on this object are carried out. Although we do not wish to overinterpret this result we note that IRAS 05189 shows peculiar characteristics at other wavelengths as well (Rigopoulou et al. 1995), so it might not be unrealistic to claim that maybe this is the case and that we are witnessing a new class of objects with similar caracteristics.

5. Line profiles

In this section the line profiles are examined to explain some of the kinematics of the gas. Although many of the spectra are too noisy to allow a good determination of their line shapes, with a few assumptions the kinematics of the CO gas can be studied. Since knowledge about the distribution of HI and CO in the ULGs is limited, the CO gas in these galaxies will be assumed to be distributed in a disk, although the rotation curve, gas temperature and surface density may be different from our own Galaxy.

Krugel et al.(1990) presented simple models to explain the kinematics of the CO gas in galaxies. The size of the galaxy plays an important role in the interpetation of the line profiles observed. The sizes of all the galaxies we observed, are assumed to be smaller than the JCMT beam, therefore a single beam contains all the CO emitting area. Under the previous assumption and according to Krugel et al. models, the shape of the profiles are very much dependent on the rotation curve and the angle of inclination i, of the galaxy. Then, three different possibilities exist:
(i) if all the CO gas is in a ring then the resulting profile shows a central deflection and two peaks at each end,
(ii) if all the CO gas is concentrated in the inner parts of the galaxy then it follows roughly a solid body rotation curve and the resulting profile will have only one component which will look rather flat-topped, and finally

(iii) if the CO gas extends to that part of the galaxy showing a flat rotation curve then the resulting profile shows again a central deflection and two peaks at each end. The deflection is more pronounced if the central rigidly rotating core is absent altogether.

Fig. 1 showed the line profiles of the galaxies observed. The absence of prominent peaks at each end of the spectra of the observed galaxies suggests that probably the gas is concentrated towards the inner parts of the galaxy. The linewidth is determined by the dynamical mass and the inclination of the galaxy. In the case of Arp 220 the linewidth is very large. (The presence of a disk in Arp 220 is suggested by infrared and optical imaging of the galaxy (Friedman, Jones and Stein 1988) as well as interferometer observations of the galaxy's CO (1 → 0) (Scoville et al. 1986) line emission). The line profile of Mrk 231 looks rather flat-topped implying that the CO gas is concentrated towards the inner parts of the galaxy which display solid body rotation and that little or no CO gas with a flat rotation curve is present. UGC 5101 profile is peaked. Central concentration of the gas is immediately implied by the shape of the line profile. However it is possible that two peaks are present although no conclusive evidence for this is available from the present data. Such double peaked profile indicates that the material extends to those areas of the galaxy that display flat rotation curves, or that the CO gas is in a ring fairly close to the nucleus. Finally the line profiles of Mrk 273 and IRAS 1720 are peaked as well but no indication for a double peak is shown. Higher resolution spectra and interferometric observations are necessary in order to investigate in more details the CO kinematics.

6. Conclusions

Results were presented from observations of the CO (J = 2→1) transition from six ultraluminous IRAS galaxies with $z < 0.05$. Four of them were previously detected in CO (J = 1→0), two of them were observed in CO (J = 2→1) for the first time. However for Arp 220 and Mrk 231 there already exist more (2–1) observations. The results can be summarized as follows:

1) The strong correlation between the IR luminosity and M_{H_2} masses found to hold in many studies of luminous infrared galaxies was affirmed using the present CO (2 –1) observations. This correlation implies a connection between the properties of molecular gas in the interstellar medium content and the infrared luminosity. The molecular hydrogen mass-to-luminosity ratio (as inferred from the values presented in Table 3) has a mean value of 4.01 similar to that measured in Galactic clouds.

2) The ratio R = (2 → 1) / (1 → 0) of the velocity integrated brightness temperatures was estimated for four galaxies of the present sample, based on our CO (2→1) and other published CO (1→0) data. Under the assumption that the angular diameter of the emitting region is the same for the two transitions then the ratio R was found to vary between 0.7 - 1.04 suggesting that conditions of the emitting region are optically thick and that the material is probably subthermally excited.

3) Weak CO (2 → 1) emission was detected from IRAS 05189. As this result seems unrealistic we encourage more observations of the same transition for this object. However IRAS 05189 shows peculiar characteristics at other wavelengths as well, therefore, it might be the case that IRAS 05189 is the exception to the rule, and that perhaps there are other ULGs following the IRAS 05189 example.

5) CO line profiles tend to be flat-topped or peaked and show no obvious sign of double peaks. This suggests that molecular material is concentrated towards the centre of the galaxy.

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