

The AMIGA sample of isolated galaxies

IX. Molecular gas properties^{★,★★}

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ABSTRACT

Aims. We characterize the molecular gas content (ISM cold phase) using CO emission of a redshift-limited subsample of isolated galaxies from the AMIGA (Analysis of the interstellar Medium of Isolated GALaxies) project in order to provide a comparison sample for studies of galaxies in different environments.

Methods. We present the ¹²CO(1–0) data for 273 AMIGA galaxies, most of them ($n = 186$) from our own observations with the IRAM 30 m and the FCRAO 14 m telescopes and the rest from the literature. We constructed a redshift-limited sample containing galaxies with $1500 \text{ km s}^{-1} < v < 5000 \text{ km s}^{-1}$ and excluded objects with morphological evidence of possible interaction. This sample ($n = 173$) is the basis for our statistical analysis. It contains galaxies with molecular gas masses, M_{H_2} , in the range of $\sim 10^8 - 10^{10} M_{\odot}$. It is dominated, both in absolute number and in detection rate, by spiral galaxies of type $T = 3-5$ (Sb-Sc). Most galaxies were observed with a single pointing towards their centers. Therefore, we performed an extrapolation to the total molecular gas mass expected in the entire disk based on the assumption of an exponential distribution. We then studied the relationships between M_{H_2} and other galactic properties (L_{B} , D_{25}^2 , L_{K} , L_{FIR} , and M_{HI}).

Results. We find correlations between M_{H_2} and L_{B} , D_{25}^2 , L_{K} , and L_{FIR} . The tightest correlation of M_{H_2} holds with L_{FIR} and, for $T = 3-5$, with L_{K} , and the poorest with D_{25}^2 . The correlations with L_{FIR} and L_{K} are very close to linearity. The correlation with L_{B} is nonlinear so that $M_{\text{H}_2}/L_{\text{B}}$ increases with L_{B} . The molecular and the atomic gas masses of our sample show no strong correlation. We find a low mean value, $\log(M_{\text{H}_2}/M_{\text{HI}}) = -0.7$ (for $T = 3-5$), and a strong decrease in this ratio with morphological type. The molecular gas column density and the surface density of the star formation rate (the Kennicutt-Schmidt law) show a tight correlation with a rough unity slope. We compare the relations of M_{H_2} with L_{B} and L_{K} found for AMIGA galaxies to samples of interacting galaxies from the literature and find an indication for an enhancement of the molecular gas in interacting galaxies of up to 0.2–0.3 dex.

Key words. galaxies: evolution – galaxies: interactions – galaxies: ISM – radio lines: ISM – radio lines: galaxies – surveys

1. Introduction

A major and longlasting debate in astronomy involves the relative roles of “nature” and “nurture” in galaxy formation and evolution (e.g. Sulentic 1976; Larson & Tinsley 1978; Joseph & Wright 1985; Bushouse 1987). Although it is broadly accepted that galaxy evolution strongly depends on the environment, the quantitative effect of “nurture” on certain galactic properties is still a matter of debate.

The molecular gas content is an important quantity of a galaxy because it is directly related to its capacity for star

formation SF. We still need to determine, however, how the environment affects the amount of the molecular gas. Galaxies in clusters (Kenney & Young 1989; Boselli et al. 1997; Scott et al., in prep.) and groups (Verdes-Montenegro et al. 1998; Leon et al. 1998) seem to have a normal molecular gas content, even though they can be highly deficient in atomic gas. On the other hand, some authors (Braine & Combes 1993; Combes et al. 1994; Casasola et al. 2004) find an enhanced molecular gas content in interacting galaxies, in contrast to the results of Perea et al. (1997), who concluded that the molecular gas content is not affected by interaction in strongly interacting pairs or Virgo cluster galaxies.

To clarify the role played by the environment, a well-defined sample of isolated galaxies is needed to serve as a zero level for studies dealing with the effect of interactions. Most previous studies investigating the properties of molecular gas in isolated

* Full Tables 1, 4 and 5 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via

<http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/534/A102>

** Appendix is available in electronic form at

<http://www.aanda.org>

and interacting galaxies (Solomon & Sage 1988; Sage 1993; Boselli et al. 1997; Nishiyama & Nakai 2001; Helfer et al. 2003; Leroy et al. 2009) have generally not defined any very clear criterion for isolation. Perea et al. (1997) carried out a CO study comparing isolated and interacting galaxies. Their sample of isolated galaxies is composed of 68 galaxies from various sources, selected in a much less rigorous way than the present study and biased towards infrared-luminous objects. The only survey explicitly focusing on isolated galaxies, and in particular on galaxies from the Catalogue of Isolated Galaxies, is the one by Sauty et al. (2003). They present the CO data of 99 optically-selected spiral galaxies with recession velocities up to $14\,000\text{ km s}^{-1}$ and briefly compare the properties of the molecular gas mass to the blue luminosity and atomic gas mass. A detailed analysis of the properties of that sample is, however, not presented there. The largest previous CO survey was the FCRAO Extragalactic CO survey (Young et al. 1995) observing ~ 300 nearby galaxies. The major difference with respect to the present study is that it did not consider the isolation of the galaxies as a criterion. Furthermore, it only contained bright galaxies (either $m_{B,\text{corr}} < 13$ mag, or $F_{60\ \mu\text{m}} > 5\text{ Jy}$ or $F_{100\ \mu\text{m}} > 100\text{ Jy}$) whereas our samples also includes fainter objects.

The project AMIGA (“Analysis of the interstellar Medium of Isolated GALaxies”, Verdes-Montenegro et al. 2005) was started to provide such a reference sample by characterizing the properties of the interstellar medium (ISM) and SF in isolated galaxies in the local Universe. It is based on the Catalogue of Isolated Galaxies (CIG Karachentseva 1973) which is composed of 1050 galaxies located in the Northern hemisphere. The AMIGA project is presented in Verdes-Montenegro et al. (2005). A considerable amount of work has been done since then in order to refine the sample. This work includes the revision of all CIG positions (Leon & Verdes-Montenegro 2003), the determination of POSS2-based morphologies and the identification of galaxies showing signs of possible interaction (Sulentic et al. 2006) and the reevaluation and quantification of the degree of isolation (Verley et al. 2007a,b). The results of this project consistently find that the AMIGA galaxies have the lowest SF activity as well as the lowest presence of active galactic nuclei (AGN) in the local Universe. This is obtained both from the far-infrared (FIR) luminosity derived from IRAS data (Lisenfeld et al. 2007), and the radio continuum emission (Leon et al. 2008), which are both SF tracers. The rate of AGN candidates, derived from IRAS colors and radio continuum emission of the AMIGA galaxies is lowest compared to similar studies from the literature (Sabater et al. 2008). Optical photometric analysis of Sb-Sc galaxies in the AMIGA sample showed that most galaxies have pseudo-bulges instead of classical bulges, and a comparison with samples of spiral galaxies selected without isolation criteria revealed that the isolated galaxies tend to host larger bars, are more symmetric, less concentrated and less clumpy (Durbala et al. 2008). These findings strongly support that the AMIGA sample represents the most isolated galaxies in the local Universe where secular evolution is dominant. Espada et al. (in prep.) study the HI content and (Espada et al. 2011) found the smallest fraction of asymmetric HI profiles in the AMIGA sample when compared with any sample yet studied.

The revised AMIGA sample is reasonably complete ($\sim 80\text{--}95\%$) down to $m_{B,\text{corr}} \leq 15.0$ mag (Verdes-Montenegro et al. 2005) and it is currently one of the largest sample of nearby isolated galaxies in the Northern hemisphere. It consists of galaxies whose structure and evolution have been driven largely or entirely by internal rather than by external forces at least during the last 3 Gyr (Verdes-Montenegro et al. 2005). The

data are being released and periodically updated at <http://amiga.iaa.es> where a Virtual Observatory interface with different query modes has been implemented.

In the present paper we present and analyze CO observations of a redshift-limited subsample of this catalogue. The goal is to characterize the properties of the molecular gas, traced by CO, of isolated galaxies and to provide a reference sample for studies investigating the role of the environment.

2. The sample

For a study of the molecular gas content we had to restrict the number of galaxies, since observation of the entire optically complete sample ($n \sim 700$) required too much telescope time. We chose to build a redshift-limited subsample by selecting galaxies with recession velocities in the range of $1500\text{--}5000\text{ km s}^{-1}$. The completeness limit of the AMIGA sample of 15 mag corresponds to blue luminosities of $\log 10(L_B/L_\odot) = 8.55$ and $\log 10(L_B/L_\odot) = 9.60$ at the distances derived for these velocities with a Hubble constant of $75\text{ km s}^{-1}\text{ Mpc}^{-1}$. The range was chosen in order to avoid (i) very nearby galaxies for which the condition of isolation is not reliable (Verley et al. 2007a) and (ii) distant galaxies which are difficult to detect in CO. The restriction in velocity provides us with a sample probing a defined volume in space.

There are 278 galaxies in this velocity range in the CIG. We have CO data for 201 of these objects, mostly from our own observations (180 galaxies) with the 30 m telescope of the Instituto de Radioastronomía Milimétrica (IRAM) at the Pico Veleta and with the 14 m Five College Radio Astronomical Observatory (FCRAO), and the rest from the literature. We then excluded those galaxies that were identified by us in a visual inspection of optical images as having signs of a possible present or past interaction (see description of Table 1 for more details on the criteria). This leaves us with 173 isolated galaxies with CO data in the velocity range between 1500 and 5000 km s^{-1} . We refer to this sample as the redshift-limited CO sample and we will use it for the statistical analysis throughout this paper.

Additionally, we have CO data for 72 galaxies outside this velocity range. Six galaxies are from our own observations (with velocities between 5000 and 5500 km s^{-1}) and the rest is from the literature. Thus, in total, we have $^{12}\text{CO}(1\text{--}0)$ data for 273 CIG galaxies. We refer to this sample as the total CO sample, and list the corresponding data in Tables 1 and 5, but we do not use it for any statistical analysis.

Recently, an update of the basic properties of the galaxies in the AMIGA sample was carried out for the blue magnitude, optical isophotal diameter D_{25} , velocity, and morphology and interaction degree based on higher resolution images (from SDSS or our own images). The details are described in Espada et al. (in prep.). In order to provide a self-contained data set for the present paper, we list in Table 1 the basic data relevant for the total CO sample. The columns are:

1. CIG: entry number in the Catalogue of Isolated Galaxies (CIG);
2. Dist: distance in Mpc, based on $H_0 = 75\text{ km s}^{-1}\text{ Mpc}^{-1}$;
3. Vel: recession velocity in km s^{-1} ;
4. D_{25} : isophotal optical major diameter at the isophotal level 25 mag arcsec^{-1} in the B -band, D_{25} , in arcmin from the Lyon Extragalactic Database (LEDA);
5. i : inclination from LEDA;

Table 1. General data for the total CO sample.

CIG	Dist	Vel	D_{25}	i	T(RC3)	Inter	$\log(L_B)$	$\log(L_{\text{FIR}})$	$\log(L_K)$
(1)	[Mpc]	[km s^{-1}]	[$''$]	[$^\circ$]	(6)	(7)	[L_\odot]	[L_\odot]	[$L_{K,\odot}$]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	96	7299	1.39	65	5	1	10.57	10.28	11.23
4	31	2310	3.29	84	5	0	10.36	10.08	10.98
6	61	4528	0.70	65	7	1	9.80	9.82	10.21
10	63	4613	1.05	63	5	0	9.78	<9.44	10.09
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Notes. The full table is available in electronic form at the CDS and from <http://amiga.iaa.es>.

6. T(RC3): morphological type T(RC3) as determined by our morphological revision, given in the RC3 numerical scale (de Vaucouleurs et al. 1991);
7. Inter: code for morphological signs of a possible interaction. 0: No signs of large distortions which cannot be clearly explained by e.g. dust. 1: At least one of the following signs of possible interaction: asymmetric, lopsided, distorted, confirmed pair in the Nasa Extragalactic Database (NED) or in Verley et al. (2007b), integral sign shape, warp, tidal features (tail, bridge, shell). 2: Merger-like morphology or superposition of two galaxies;
8. $\log(L_B)$: decimal logarithm of the blue luminosity, L_B , in units of solar bolometric luminosities. We calculated L_B , from the flux, f_B , as $L_B = \nu f_B$, where ν is the central frequency of the blue band;
9. $\log(L_{\text{FIR}})$: decimal logarithm of the far-infrared luminosity in units of solar bolometric luminosities, taken from Lisenfeld et al. (2007) and adapted to the revised distances used in the present paper. L_{FIR} is computed from the IRAS fluxes at 60 and 100 μm , F_{60} and F_{100} , as $\log(L_{\text{FIR}}/L_\odot) = \log(F_{\text{IR}}) + 2\log(D) + 19.495$, where D is distance in Mpc and $F_{\text{IR}} = 1.26 \times 10^{-14} (2.58F_{60} + F_{100}) \text{ W m}^{-2}$ (Helou et al. 1988);
10. $\log(L_K)$: decimal logarithm of the luminosity in the K -band, in units of the solar luminosity in the K_S -band ($L_{K,\odot} = 5.0735 \times 10^{32} \text{ erg s}^{-1}$), calculated from the extrapolated magnitude in the K_S (2.17 μm) band from the 2MASS Extended Source Catalogue (Jarrett et al. 2000). The magnitudes were available for 250 galaxies of our sample. We calculated the K_S luminosity, L_K , from the total (extrapolated) K_S flux, f_K , as $L_K = \nu f_K(\nu)$, where ν is the central frequency of the K_S -band. L_K is a good measure of the total stellar mass.

In Fig. 1 we present some of the basic characteristics of the CO samples and compare them to those of the optically complete sample (Verdes-Montenegro et al. 2005). The latter ($n = 712$) is composed of CIG galaxies with m_B in the range of 11–15 mag and is 80–95% complete. The main difference between the CO and the optically complete sample is the larger spread in velocity of the latter (Fig. 1a). The CO samples are at a lower velocity, especially the redshift-restricted sample. This leads to a slightly lower optical luminosity (Fig. 1b) of the CO samples since the number of luminous objects is higher at larger distances due to the Malmquist bias.

The distribution of the morphological types (Fig. 1c) is very similar in all the three samples. All samples are dominated by spiral galaxies. The relative number of early type galaxies ($T = (-5) - 0$) is 8% for the optically complete sample and 13% for the CO redshift-restricted sample. The distribution is peaked around galaxies with types $T = 3 - 5$ (63% for the optically complete sample and 51% for the CO redshift-restricted sample).

3. CO observations and analysis

We carried out CO(1–0) observations with the FCRAO and with the IRAM 30 m telescope. We observed galaxies with isophotal diameters $D_{25} < 100''$ at the 30 m telescope and galaxies with $D_{25} \geq 100''$ at the 14 m FCRAO telescope. In this way we tried to optimize the agreement between beam size and optical diameters and minimize the fraction of missing flux in the observations done with a single pointing. We observed 100 galaxies at the FCRAO radio-telescope and 101 at the IRAM 30 m telescope. In order to check the consistency of the results we observed 15 galaxies at both telescopes.

3.1. Observations

3.1.1. IRAM 30 m telescope

We observed the $^{12}\text{CO}(1-0)$ line at 115 GHz with the IRAM 30-m telescope on Pico Veleta using the dual polarization receivers A100 and B100, together with the 512×1 MHz filterbanks. The observations were done in wobbler switching mode with a wobbler throw of $120''$ in azimuthal direction. Pointing was monitored on nearby quasars every 60–90 min. The integration time on source was typically 0.5 to 1.5 h. The mean system temperatures was 320 K on the T_A^* scale. All CO spectra and intensities are presented on the main beam temperature scale (T_{mb}) which is defined as $T_{\text{mb}} = (F_{\text{eff}}/B_{\text{eff}}) \times T_A^*$. The IRAM forward efficiency, F_{eff} , was 0.95 and the beam efficiency, B_{eff} , 0.75. The peak intensities of our sources ranged between about 10 and 80 mK (T_{mb}).

Most galaxies were observed at the central position with a single pointing. The galaxies with the strongest emission at the center (19 galaxies) were mapped along the major axis with a spacing of $15''$, until a root mean square (rms) noise of about 3 mK was reached for a velocity resolution of 10.6 km s^{-1} .

3.1.2. FCRAO 14 m telescope

The observations at the FCRAO were done with the receiver SEQUOIA, a 4×4 pixel array operating from 85 to 115 GHz. We used the so called “beam switching” mode, in which the telescope switches position between the source and a reference position $89.2''$ apart in azimuth. Two of the pixels in the array alternated between the ON- and the OFF-position, doubling in this way the effective integration time.

The typical observing time per object was about 2 h. The pointing was checked between the observations of different sources using a nearby quasar. The mean system temperatures was 380 K (on the T_A^* scale). All CO spectra and luminosities are presented on the main beam temperature scale (T_{mb}) which is defined as $T_{\text{mb}} = T_A^*/B_{\text{eff}}$. The main beam efficiency is $B_{\text{eff}} = 0.45$. We observed each galaxy with one pointing at

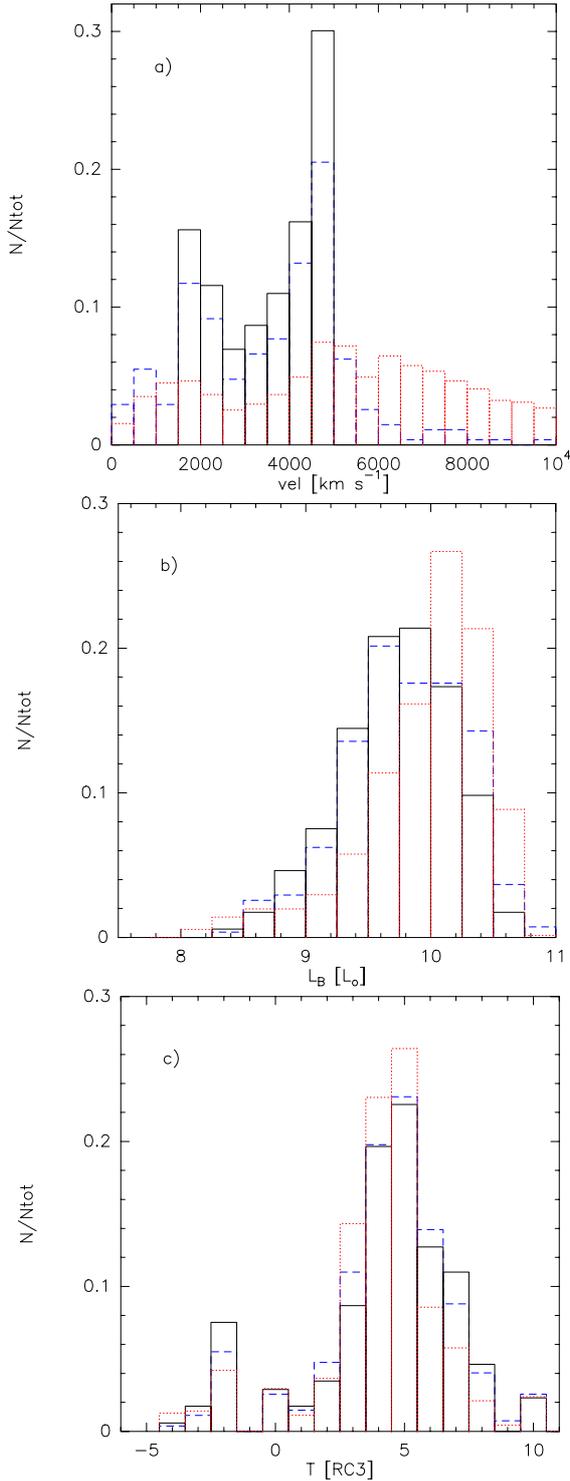


Fig. 1. Basic properties (normalized distributions) of the redshift-restricted CO sample ($n = 173$, full black line), total CO sample, excluding possibly interacting objects ($n = 234$, dashed blue line) as well as the optically complete sample ($n = 712$, Verdes-Montenegro et al. 2005, dotted red line). **a)** Recession velocity, **b)** optical luminosity, $\log(L_B)$ and **c)** morphological type (T(RC3), as in the RC3 catalogue).

their central position. The peak intensities of our sources ranged between about 10 and 80 mK (T_{mb}).

3.1.3. Literature data

We furthermore searched the literature and found CO(1–0) data for 131 objects, 87 of them had not been observed by us. We list

Table 2. List of papers from which the CO data have been compiled.

Bibl. code	Article	Telescope ¹	N
1	This work	1, 2	189
2	Young et al. (1995)	2, 5	25
3	Braine & Combes (1993)	1	11
4	Sauty et al. (2003)	1, 3, 5	99
5	Elfhag et al. (1996)	3, 4	15
6	Sage (1993)	5	7

Notes. ⁽¹⁾ The codes for the telescopes are listed in Table 3.

Table 3. Main parameters of the used radio-telescopes.

Code	Radio-Telescope	Diameter	θ_{HPBW} (115 GHz)	Jy/K ¹
1	IRAM	30 m	21''	5
2	FCRAO	14 m	45''	20
3	SEST	15 m	43''	19
4	Onsala	20 m	33''	12
5	NRAO Kitt-Peak	12 m	55''	32

Notes. ⁽¹⁾ The conversion factor from T_{mb} in K to flux in Jy.

the references for these data in Table 2. Some galaxies were observed at several telescopes. Table 3 provides information about the telescopes used in the different surveys: the antenna size (Col. 3), the half power beam width (HPBW) (Col. 4) and the conversion factor Jy/K (on the T_{mb} scale) at 115 GHz (Col. 5).

3.2. Data reduction

The data from both telescopes were reduced in the standard way using the CLASS software in the GILDAS package¹. The data reduction consisted in dismissing poor scans, flagging bad channels, subtracting a baseline and averaging the spectra for the same object and position. In most cases a constant baseline was subtracted and only in a few cases the subtraction of a linear baseline was required.

3.3. Spectra and integrated intensities

The CO(1–0) profiles of the detections and tentative detections observed by us at the IRAM 30 m and FCRAO 14 m are shown in Appendix A (Figs. A.1 and A.2, respectively). The spectral shapes observed are very diverse. Both single and double peaked lines are present and the line widths span a wide range.

The velocity integrated intensity, $I_{\text{CO}} = \int T_{\text{mb}} dv$ (in K km s⁻¹), was calculated from the spectra with a velocity resolution of 10.6 km s⁻¹ for the IRAM spectra, respectively 13.1 km s⁻¹ for the FCRAO spectra by summing up all channels with significant emission. Its error was calculated as:

$$\text{error}(I_{\text{CO}}) = \sigma(W_{\text{CO}} \delta V_{\text{CO}})^{1/2} [\text{K km s}^{-1}],$$

where σ is the rms noise of the spectrum, W_{CO} is the CO line width, and δV_{CO} is the spectral resolution. For undetected galaxies, we calculate a 3σ upper limit, assuming a line width of 300 km s⁻¹, as:

$$I_{\text{u.l.}}(\text{CO}) = 3 \times \sigma(300\delta V_{\text{CO}})^{1/2} [\text{K km s}^{-1}].$$

In Table 4 we list the following items:

- entry number in the Catalogue of Isolated Galaxies (CIG).
An asterisk added to the number means that the detection is

¹ <http://www.iram.fr/IRAMFR/GILDAS>

marginal. In our statistical analysis we treat marginal detections as upper limits;

2. off. α : RA offset from the center in arcsec;
3. off. δ : Declination offset from the center in arcsec;
4. rms: root mean square noise in mK for a velocity resolution of 10.6 km s^{-1} (IRAM), respectively 13.1 km s^{-1} (FCRAO);
5. I_{CO} : velocity integrated CO line temperature $\int T_{\text{mb}} dv$, in K km s^{-1} , and its error;
6. V_{CO} : mean velocity of the CO line, in km s^{-1} ;
7. W_{CO} : zero line-width of the CO spectrum, in km s^{-1} ;
8. Tel: radio-telescope code, as listed in Table 3.

3.4. Comparison between IRAM and FCRAO data

In order to check the relative calibration between the IRAM 30 m and the FCRAO 14 m telescope and to guarantee that these two data sets are comparable, we observed 15 galaxies with both telescopes. We expect a ratio of the velocity integrated intensities of $I_{\text{CO-IRAM}}/I_{\text{CO-FCRAO}} = 1$ for emission homogeneously filling the beams, and $I_{\text{CO-IRAM}}/I_{\text{CO-FCRAO}} = (\Theta_{\text{FCRAO}}/\Theta_{\text{IRAM}})^2 = 4.5$, where Θ_{FCRAO} and Θ_{IRAM} are the *FWHM* of the respective beams, for a point-like emission.

Four galaxies (CIG 66, 181, 281 and 330) were detected at both telescopes. The ratios of $I_{\text{CO-IRAM}}/I_{\text{CO-FCRAO}}$ range between 1.1 and 2.3, consistent with the value expected for slightly concentrated emission. Six galaxies were detected at IRAM, but only tentatively detected (CIG 176, CIG 355) or undetected (CIG 217, CIG 561, CIG 609, CIG 622) at the FCRAO. The lower limit for $I_{\text{CO-IRAM}}/I_{\text{CO-FCRAO}}$ in five cases was between 0.94 and 3.6, consistent with the expected range of values. For CIG 217 this value is higher ($I_{\text{CO-IRAM}}/I_{\text{CO-FCRAO}} = 6.1$) than the theoretical upper limit. Since the detection at IRAM has a high signal-to-noise ratio, the most likely reason is an underestimate of the upper limit of the FCRAO data. There is one object with a detection at the FCRAO and only a tentative detection at IRAM (CIG 433), and one with a nondetection at IRAM (CIG 268). The ratio of the intensities in both cases is $I_{\text{CO-IRAM}}/I_{\text{CO-FCRAO}} = 0.3$, indicating an underestimate in the IRAM data. In the remaining three cases, both observations were either no detection or tentative detections.

We conclude that there is very good agreement between the detected values at both telescopes, and in most cases (with the exception of three galaxies) also for objects only detected at one telescope. This gives us confidence that the calibration of the two data sets is consistent.

3.5. Calculation of the molecular gas mass

The molecular gas mass (M_{H_2}) is calculated using a Galactic conversion factor of $N(\text{H}_2)/I_{\text{CO}} = 2.0 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ (e.g. Dickman et al. 1986) yielding:

$$M_{\text{H}_2} [M_{\odot}] = 75 I_{\text{CO}} D^2 \Omega, \quad (1)$$

where I_{CO} is the velocity integrated CO line intensity in K km s^{-1} , D is the distance in Mpc and Ω is the area covered by the observations in arcsec^2 (i.e. $\Omega = 1.13 \Theta_{\text{B}}^2$ for a single pointing with a Gaussian beam of *FWHM* Θ_{B}). We do not include the mass of heavy metal (mostly helium) in the molecular gas mass.

Most of our objects were observed at the central position in a single pointing since the mapping of the entire galaxy would have been too time-consuming. We therefore might have missed part of the CO emission for galaxies where the emission is more extended than the beam. This fraction depends on the galaxy

size, inclination and on the telescope beams. It is thus necessary to correct for this loss, and we do this by extrapolating M_{H_2} observed in the central beam to the total mass in the galaxy. In the next subsection we explain how we carried out this correction.

3.5.1. Aperture correction

In order to apply an aperture correction, we need to predict the distribution of the CO emission. CO maps of nearby spiral galaxies (Nishiyama et al. 2001; Regan et al. 2001; Leroy et al. 2008) have shown that the radial distribution of $I_{\text{CO}}(r)$ in galaxies can be well described by an exponential function with a scale length r_e :

$$I_{\text{CO}}(r) = I_0 \exp(-r/r_e). \quad (2)$$

The CO scale length, r_e , is well correlated and similar to the optical exponential scale length (Regan et al. 2001; Leroy et al. 2008). It also correlates, although less tightly, with the optical radius at the 25mag isophote, r_{25} . Leroy et al. (2008) derived for spiral galaxies from the THINGS survey a mean value of $\alpha = r_e/r_{25} = 0.2$. We derived the same mean value for α from the data of Regan et al. (2001) for 15 spiral galaxies observed in the BIMA Survey of Nearby Galaxies (BIMA-SONG) and from the data of Nishiyama & Nakai (2001) for 25 spiral galaxies observed with the Nobeyama 45 m telescope. We also used the data of Young et al. (1995), who studied the molecular gas content and distribution in a sample of 300 nearby galaxies, to derive the r_e . They found a mean ratio between the effective CO diameter, D_{CO} , the diameter within which 70% of the CO emission is situated, and the optical diameter of $D_{\text{CO}}/D_{25} = 0.5$. For an exponential distribution one can derive that $D_{\text{CO}} \times 0.5 = 2.5 r_e$. Thus, their data also yield $r_e/r_{25} = \frac{D_{\text{CO}} \times 0.5 / 2.5}{D_{25} \times 0.5} = \frac{0.5}{2.5} = 0.2$.

Finally, we use the data of the 19 galaxies (all of them with morphological type $T \geq 2$) mapped along the major axis with the IRAM 30 m telescope as a further test. Although our data is not sufficiently detailed to fit the radial distribution (we have only 3–5 detected spectra along the major axis), we can use it to test whether (i) an exponential distribution is a reasonable description of the CO distribution, (ii) the scale length derived by other studies is in agreement with our data, and (iii) the predictions for the extrapolated M_{H_2} are in agreement with our mapped values.

For the first two tests, we fitted an exponential distribution independently to each side of the CO distribution along the major axis. From the 38 resulting fits, there were only six cases where no exponential fit could be applied within the error bars. In five cases we derived $\alpha \geq 0.4$, in seven cases $0.4 < \alpha < 0.25$, in three cases $\alpha < 0.15$ and in 17 cases, the majority, $0.15 \leq \alpha \leq 0.25$. Thus, our data are in general consistent with the value of α found by other studies.

In summary, we conclude that an exponential distribution of the molecular gas distribution with $\alpha = r_e/r_{25} = 0.2$ is a good approximation based on the CO maps for nearby spiral galaxies available up to date and also consistent with our data. We adopt the same value for both spiral galaxies and early type galaxies. In early-type galaxies, the molecular gas extent is much less known. However, for our study, this uncertainty is not important because the number of objects with $T \leq 0$ is low ($n = 23$, with eight detections) and we focus on our results and conclusions on spiral galaxies, in particular of types $T = 3$ –5, which dominate the sample.

We now use these results to calculate the aperture correction which we define as the ratio between the total (extrapolated)

Table 4. Velocity integrated $^{12}\text{CO}(1-0)$ line intensities, mean velocity and line widths for the CIG galaxies observed by us.

CIG	Off. α	Off. δ	rms	I_{CO}	V_{CO}	W_{CO}	Tel.
(1)	['']	['']	[mK]	[K km s $^{-1}$]	[km s $^{-1}$]	[km s $^{-1}$]	(8)
10*	0	0	3.47	0.50 ± 0.15	4980	180	1
27	0	0	4.21	3.54 ± 0.23	4586	287	1
27	13	8	7.21	<1.22	–	–	1
29*	0	0	5.24	0.49 ± 0.16	4162	92	1
...

Notes. The full table is available in electronic form at the CDS and from <http://amiga.iaa.es>.

molecular gas mass M_{H_2} , and the molecular gas mass in the central pointing, $M_{\text{H}_2, \text{center}}$,

$$f_{\text{ap}} = M_{\text{H}_2} / M_{\text{H}_2, \text{center}}. \quad (3)$$

The total molecular gas mass is calculated by spatially integrating $I_{\text{CO}}(r)$ from Eq. (2) and using Eq. (1). This yields:

$$\begin{aligned} M_{\text{H}_2} [M_{\odot}] &= 75D^2 \int_0^{\infty} I(r) 2\pi dr \\ &= 75D^2 \int_0^{\infty} I_0 \exp(-r/r_e) 2\pi dr = 75D^2 I_0 2\pi r_e^2. \end{aligned} \quad (4)$$

Similarly, we calculate $M_{\text{H}_2, \text{center}}$ by convolving the exponential CO intensity distribution with a Gaussian beam. This yields:

$$\begin{aligned} M_{\text{H}_2, \text{center}} [M_{\odot}] &= 75D^2 4I_0 \int_0^{\infty} dx \int_0^{\infty} dy \exp\left(-\ln(2) \left[\left(\frac{2x}{\Theta_B} \right)^2 \right. \right. \\ &\quad \left. \left. + \left(\frac{2y \cos(i)}{\Theta_B} \right)^2 \right] \right) \exp\left(-\frac{\sqrt{x^2 + y^2}}{r_e}\right), \end{aligned} \quad (5)$$

where i is the inclination of the disk. The integration of Eq. (5) is carried out numerically.

Thus, the correction factor, $f_{\text{ap}} = M_{\text{H}_2} / M_{\text{H}_2, \text{center}}$, depends on the ratio of the scale length and the beam size, r_e / Θ_B , as well as the galaxy inclination i . Figure 2 shows the distribution of f_{ap} for the galaxies in our sample. The correction factors are generally low: 81% of the galaxies have $f_{\text{ap}} < 2$, and 92% $f_{\text{ap}} < 3$. Only nine galaxies have a correction factor above 5. All of them are nearby ($v < 1000$ km s $^{-1}$) galaxies with a large angular size (between 4' and 20') that are not included in our redshift-limited sample.

In order to carry out test (iii) we compared for the 19 galaxies, that were mapped along their major axis with the IRAM 30 m telescope, the extrapolated M_{H_2} to the mapped molecular gas mass which we extrapolated to the mass in the entire disk by assuming azimuthal symmetry ($M_{\text{H}_2, \text{map, extra}}$). Figure 3 presents the ratio of these two masses as a function of D_{25} and i . For most objects, both masses agree reasonably well, with ratios ranging between 0.5 and 1.3. There are only two outliers, with ratios around 2. These galaxies (CIG 84 and CIG 28) have a very flat CO distribution along the major axis so that our extrapolation, assuming an exponentially decreasing distribution, underestimates the true amount of molecular gas. No trend with neither D_{25} nor the inclination is seen, showing that no apparent bias is introduced by the aperture correction. The mean mass ratio is 1.0, with a standard deviation of 0.3.

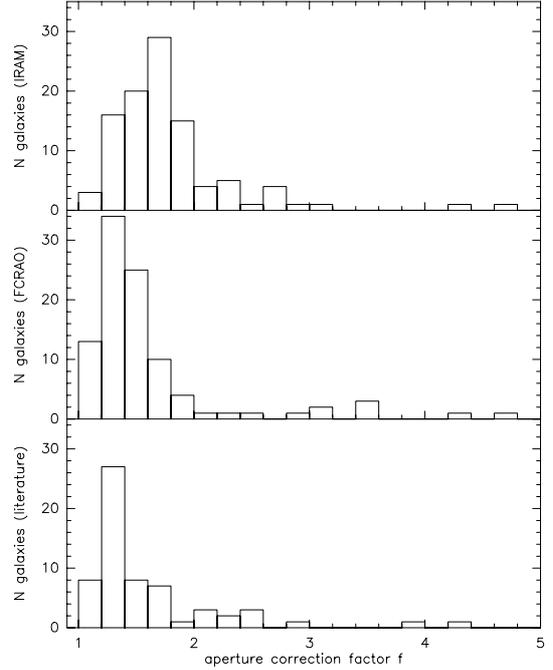


Fig. 2. Histogram of the aperture correction factor, f_{ap} , for galaxies observed by us with the IRAM 30 m telescope (*upper panel*), with FCRAO (*middle panel*) and for galaxies taken from the literature (*lower panel*).

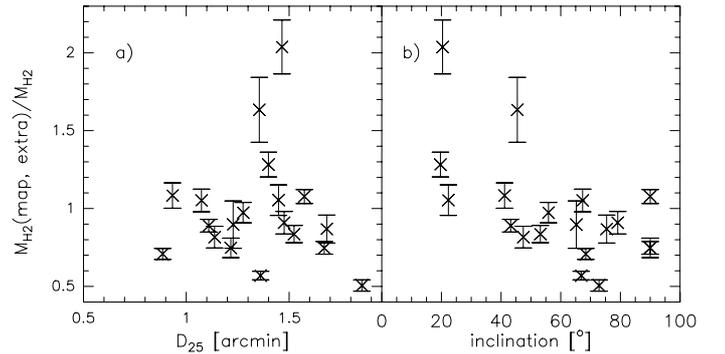


Fig. 3. Ratio between the molecular gas mass, mapped along the major axis with the IRAM 30 m telescope, and extrapolated to the entire disk assuming azimuthal symmetry ($M_{\text{H}_2, \text{map, extra}}$) and the molecular gas mass extrapolated from the central pointing as explained in Sect. 3.5.1 (M_{H_2}) as a function of diameter **a)** and galaxy inclination **b)**.

4. Results

4.1. Molecular gas content

In Table 5 we list M_{H_2} for the individual galaxies. If observations from different references were available for a single galaxy, we inspected the spectra and discarded those of poorer quality. In case of similarly good data we gave preference to mapped observations or to observations from the telescope with a larger beam in order to avoid flux loss. For the 44 objects that had data from the literature and were also observed by us, our data was in general of better quality, with the exception of three objects (CIG 512, CIG 604, CIG 626). The columns in Table 5 are:

1. CIG: entry number in the Catalogue of Isolated Galaxies (CIG);
2. $\log(M_{\text{H}_2})_{\text{center}}$: decimal logarithm of M_{H_2} towards the central pointing in solar masses, derived from Eq. (1). An asterix

Table 5. Molecular gas mass.

CIG	$\log(M_{\text{H}_2}) [M_\odot]$			Tel.	Ref.
	center	mapped	extrapol.		
(1)	(2)	(3)	(4)	(5)	(6)
1	9.47	0	9.58	3	4
4	8.96	9.08	9.26	2	2
6	<8.14	0	<8.14	5	4
10	7.88*	0	8.13*	1	1
....

Notes. The full table is available in electronic form at the CDS and from <http://amiga.iaa.es>.

denotes tentative detections that are treated as upper limits in the statistical analysis;

3. $\log(M_{\text{H}_2})$ mapped: decimal logarithm of the mapped M_{H_2} in solar masses, calculated in the following way: for the data from the literature, the angular separation between the individual pointings was always larger than the beam size so that the total M_{H_2} could be calculated as the sum of the individual pointings. For our own observations with the IRAM 30 m telescope, the spacing between the individual pointing was $15''$, which is smaller than the $FWHM$ of the beam ($21''$) so that in this case we had to take the overlap of the individual pointings into account. We calculated the mapped M_{H_2} from Eq. (1) where I_{CO} is taken as the mean value of the different pointings, and Ω is the total area covered by the mapping, approximated as $21'' \times 36''$, $21'' \times 51''$, $21'' \times 66''$, $21'' \times 81''$ for 2, 3, 4, and 5 pointings, respectively;
4. $\log(M_{\text{H}_2})$ extrapol.: total (extrapolated) M_{H_2} in solar masses, calculated as described in Sect. 3.5.1. An asterisk denotes tentative detections that are treated as upper limits in the statistical analysis;
5. Tel.: radio-telescope code, as in Table 3;
6. Ref.: bibliographic code, as in Table 2.

Figure 4 shows the distribution of $\log(M_{\text{H}_2})^2$, for detections in the total and redshift-limited CO samples and for nondetections in the latter. The distributions in the total and in the redshift-limited samples are very similar. The mean M_{H_2} of the redshift-limited sample is $\log(M_{\text{H}_2}) = 8.30 \pm 0.08$ (see Table 6), calculated with the package ASURV that takes into account the upper limits. Here and throughout the paper we use the ASURV³ package which applies survival analysis in the presence of upper or lower limits and calculates the mean value based on the Kaplan-Meier estimator.

Figure 5 shows the distribution of the molecular gas mass as a function of the morphological type. The mean and median values are listed in Table 6. Our sample is dominated by spiral galaxies of type $T = 3-5$ (Sb-Sc). Not only is the total number of objects greatest in this range, but also the detection rate. Therefore, we can derive the most reliable results for these types. Both for earlier and for later types, the detection rates are very low, making a detailed analysis difficult. The molecular gas mass is largest for spiral galaxies of $T = 3-5$, and decreases both for earlier and later types. There are eight early-type galaxies, of type S0 and S0a, with detections in M_{H_2} , and five of them

² Here, and in the following, we always use to the extrapolated molecular gas mass in our analysis and denote it M_{H_2} for simplicity.

³ Astronomy Survival Analysis (ASURV) Rev. 1.1 is a generalized statistical package that implements the methods presented by Feigelson & Nelson (1985) and Isobe et al. (1986), and is described in detail in Isobe et al. (1990) and Lavalley et al. (1992).

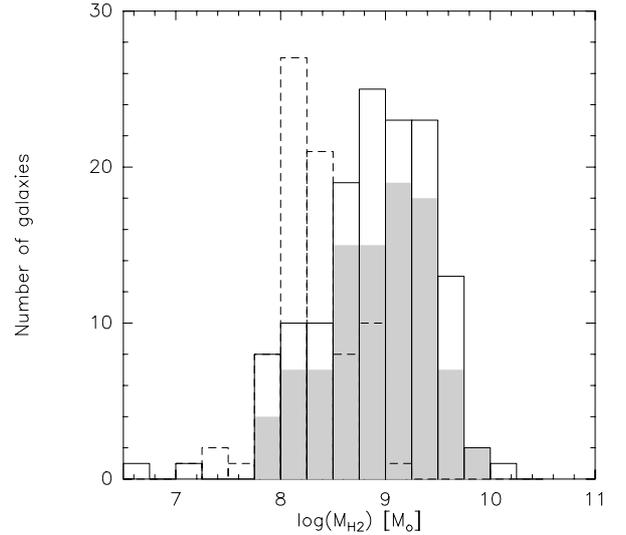


Fig. 4. Histogram of the molecular gas mass, M_{H_2} . Galaxies flagged as potentially interacting were excluded. The full line corresponds to all detections ($n = 131$), the gray filled histogram shows detections in the redshift limited sample ($n = 89$) and the dashed lines shows tentative or nondetections in the redshift-limited sample ($n = 84$).

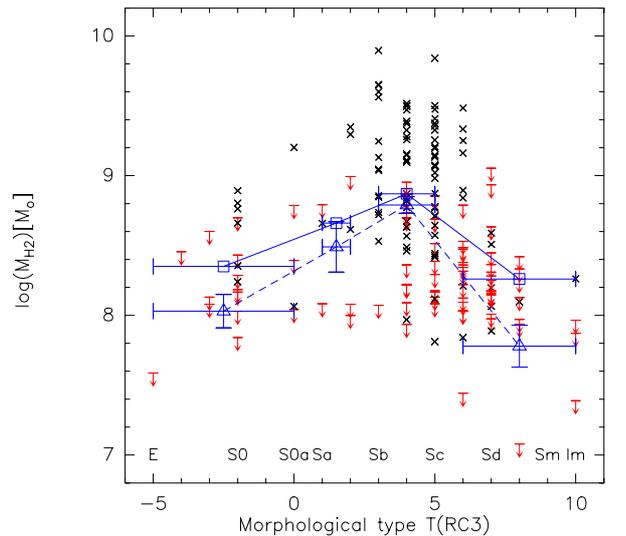


Fig. 5. The molecular gas mass for the redshift-limited sample as a function of morphological type. Triangles denote the mean value and its error for a range of morphological types and squares the median value, as listed in Table 6. The error bars in the x -direction denote the range of morphological types over which the mean and median have been taken.

have unusually high molecular gas masses in the range of those for spiral galaxies (CIG 332, CIG 481, CIG 498, CIG 733 and CIG 1015).

4.2. Relation of M_{H_2} to other parameters

In the following we investigate the relations between M_{H_2} and L_{B} , D_{25} , L_{FIR} , L_{K} and M_{HI} . The first two quantities (L_{B} , D_{25}) were chosen because they are in general available for any galaxy and are therefore useful to predict the expected M_{H_2} . L_{FIR} is very closely related to M_{H_2} because of their common relation to SF. L_{K} is dominated by the emission of low-mass stars which are the result of the long-term SF history of an object and determine the gravitational potential which influences the SF activity.

Table 6. Mean and median values.

Sample	$\langle \log(M_{\text{H}_2}) \rangle$	$\langle \log\left(\frac{M_{\text{H}_2}}{L_B}\right) \rangle$	$\langle \log\left(\frac{M_{\text{H}_2}}{D_{25}^2}\right) \rangle$	$\langle \log\left(\frac{M_{\text{H}_2}}{L_K}\right) \rangle$	$\langle \log\left(\frac{M_{\text{H}_2}}{M_{\text{HI}}}\right) \rangle$	$\langle \log\left(\frac{L_{\text{FIR}}}{M_{\text{H}_2}}\right) \rangle$	$\langle \log(\text{SFE}) \rangle$
	$[M_\odot]$ median	$[M_\odot/L_\odot]$ median	$[M_\odot/\text{kpc}^2]$ median	$[M_\odot/L_{K,\odot}]$ median	median	$[L_\odot/M_\odot]$ median	$[\text{yr}^{-1}]$ median
(1)	n/n_{up} (2)	n/n_{up} (3)	n/n_{up} (4)	n/n_{up} (5)	n/n_{up} (6)	n/n_{up} (7)	n/n_{up} (8)
E-Im ($T = (-5)-10$)	8.30 ± 0.08 8.61 173/79	-1.28 ± 0.04 -1-10 173/79	6.00 ± 0.05 6.22 173/79	-1.87 ± 0.05 -1.58 157/65	-0.94 ± 0.05 -0.73 153/63	0.72 ± 0.03 0.64 97/22	-8.94 -9.02 97/22
E-Im ($f_{\text{ap}} < 1.5$)	8.30 ± 0.12 8.51 76/42	-1.29 ± 0.06 -1.07 76/42	6.06 ± 0.07 6.29 76/42	-1.80 ± 0.06 -1.55 65/33	-0.96 ± 0.08 -0.76 66/33	0.80 ± 0.06 0.69 39/12	-8.86 -8.97 39/12
E-S0a ($T = (-5)-0$)	8.03 ± 0.12 8.35 23/15	-1.45 ± 0.11 -1.16 23/15	5.79 ± 0.13 6.27 23/15	-2.32 ± 0.10 -2.06 22/15	-0.46 ± 0.21 -0.25 8/3	0.95 ± 0.08 0.94 6/0	-8.71 -8.72 6/0
Sa - Sab ($T = 1-2$)	8.49 ± 0.18 8.66 9/5	-1.41 ± 0.19 -1.32 9/5	5.76 ± 0.20 5.89 9/5	-2.27 ± 0.19 -2.06 9/5	-0.58 ± 0.21 -0.53 8/4	0.69 ± 0.06 0.63 6/3	-8.97 -9.03 6/3
Sb-Sc ($T = 3-5$)	8.79 ± 0.06 8.87 88/21	-1.10 ± 0.04 -1.01 88/21	6.26 ± 0.05 6.37 88/21	-1.66 ± 0.04 -1.58 87/20	-0.72 ± 0.06 -0.60 85/19	0.63 ± 0.03 0.62 68/10	-9.03 -9.04 68/10
Scd-Im ($T = 6-10$)	7.78 ± 0.15 8.26 53/38	-1.41 ± 0.05 -1.15 53/38	5.79 ± 0.05 6.01 53/38	-1.62 ± 0.06 -1.37 39/25	-1.38 ± 0.07 -1.07 52/37	0.99 ± 0.09 0.63 17/9	-8.67 -9.03 17/9

Notes. Mean value and its error calculated with the program ASURV for different subsamples, and (below) median value (calculated treating the upper limits as detections). For the mean and median value of $\log(M_{\text{H}_2}/L_{\text{FIR}})$ and $\log(M_{\text{H}_2}/M_{\text{HI}})$ only galaxies with detection in L_{FIR} or M_{HI} , respectively, were taken into account, since ASURV cannot handle both upper and lower limits. Below: total number of galaxies and number of upper limits in M_{H_2} taken into account for the means and median.

Finally, we compare M_{H_2} to M_{HI} in order to derive the molecular-to-atomic gas mass ratio as a function of morphological type.

The results of the regression analysis as well as the Spearman rho correlation coefficient derived in this section are listed in Table 7, and the mean and median values of the ratios for different subsamples are in Table 6. We use the package ASURV to calculate the bisector regression line applying the Schmitt's binning method (Schmitt 1985) as the only method offered by ASURV able to deal with censored data in both the dependent and the independent variable⁴.

4.2.1. Optical luminosity

Figure 6 shows the relation between M_{H_2} and L_B , for the the entire redshift-limited sample and for subsamples of different morphological types, together with the the best-fit bisector regression lines. The high number of upper limits for galaxies of type $T = (-5)-2$ and $T = 6-10$ impedes the calculation of a reliable regression line for these individual subgroups. However, we note that there is no apparent deviation from the mean best-fit regression for all morphological types for these two groups. A slope considerably larger than 1 is found for the correlation between M_{H_2} and L_B , in agreement with Perea et al. (1997). This means that the ratio M_{H_2}/L_B tends to increase with L_B . Even though the scatter around the best-fit is large, so that no strong correlation exists between M_{H_2}/L_B and L_B , we confirm the variation of M_{H_2}/L_B by finding that the mean values is indeed higher for high L_B than for low L_B : for galaxies (all morphological types) with $L_B < 10^{10} L_\odot$ ($n = 123$ galaxies, $n = 68$ upper limits) we obtain $M_{\text{H}_2}/L_B = -1.36 \pm 0.05$ and for galaxies with $L_B \geq 10^{10} L_\odot$ ($n/n = 50/11$) $M_{\text{H}_2}/L_B = -1.10 \pm 0.06$.

⁴ The Schmitt method was partially reimplemented and wrapped into Python. It can be found at <http://amiga.iaa.es/software/python-asurv>

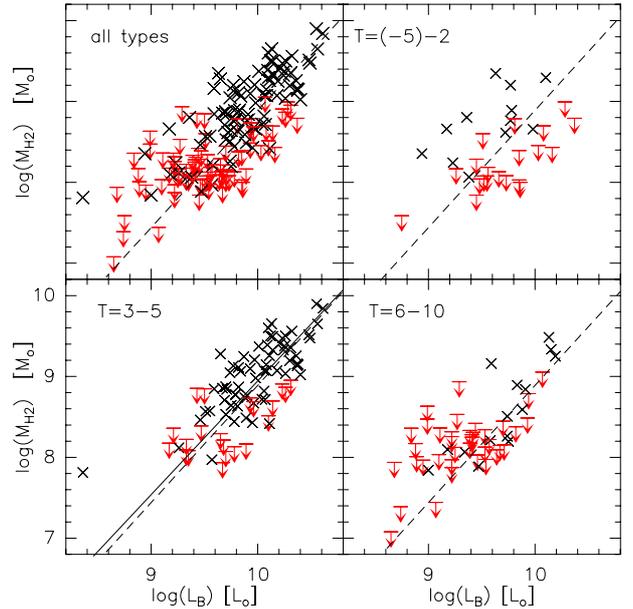


Fig. 6. M_{H_2} vs. L_B for the redshift-limited CO sample ($n = 173$), including all morphological types, and for groups of different morphological types. The dashed line gives the best fit bisector (derived with ASURV) for all morphological types and the solid line is the best fit for the $T = 3-5$ sample.

The corresponding numbers for the $T = 3-5$ subsample are -1.16 ± 0.06 ($L_B < 10^{10} L_\odot$, $n/n = 48/16$) and -1.04 ± 0.05 ($L_B \geq 10^{10} L_\odot$, $n/n = 40/5$). This trend has to be taken into account when using this ratio as an indicator of an enhancement of M_{H_2} .

The ratio between M_{H_2} and L_B is shown in Fig. 7 as a function of morphological type. The values are listed in Table 6.

Table 7. Correlation analysis.

Sample	n	n_{up}	Slope (bisector)	Intercept (bisector)	Slope (M_{H_2} dep.)	Intercept (M_{H_2} dep.)	Corr. coeff r
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
M_{H_2} vs. L_{B}							
E-Im ($T = (-5)-10$)	173	79	1.45 ± 0.08	-5.61 ± 0.77	1.12 ± 0.08	-2.43 ± 0.83	0.66
E-Im ($f_{\text{ap}} < 1.5$)*	76	42	1.32 ± 0.10	-4.27 ± 0.94	1.06 ± 0.10	-1.79 ± 0.98	0.63
Sb-Sc ($T = 3-5$)	88	21	1.41 ± 0.10	-5.12 ± 0.97	1.06 ± 0.10	-1.69 ± 1.02	0.65
M_{H_2} vs. D_{25}^2							
E-Im ($T = (-5)-10$)	173	79	1.41 ± 0.05	5.10 ± 0.50	0.88 ± 0.09	6.36 ± 0.23	0.52
E-Im ($f_{\text{ap}} < 1.5$)*	76	42	1.32 ± 0.08	5.47 ± 0.71	0.91 ± 0.11	6.38 ± 0.26	0.47
Sb-Sc (3-5)	88	21	1.31 ± 0.09	5.50 ± 0.93	0.79 ± 0.10	6.82 ± 0.27	0.53
M_{H_2} vs. L_{K}							
E-Im ($T = (-5)-10$)	157	65	1.05 ± 0.07	-2.27 ± 0.72	0.72 ± 0.07	1.13 ± 0.74	0.64
E-Im ($f_{\text{ap}} < 1.5$)*	65	33	0.99 ± 0.09	-1.54 ± 0.96	0.69 ± 0.09	1.41 ± 0.95	0.66
Sb-Sc ($T = 3-5$)	87	20	1.18 ± 0.07	-3.49 ± 0.78	0.95 ± 0.08	-1.14 ± 0.85	0.74
M_{H_2} vs. L_{FIR}							
E-Im ($T = (-5)-10$)	172	97	1.16 ± 0.08	-2.14 ± 0.72	0.98 ± 0.06	-0.46 ± 0.61	0.80
E-Im ($f_{\text{ap}} < 1.5$)*	75	48	1.15 ± 0.13	-2.09 ± 1.23	0.89 ± 0.11	0.28 ± 1.04	0.71
Sb-Sc ($T = 3-5$)	88	30	1.04 ± 0.06	-1.00 ± 0.55	0.90 ± 0.06	0.29 ± 0.58	0.82
Σ_{SFR} vs. Σ_{H_2}							
E-Im ($T = (-5)-10$)	172	97	0.89 ± 0.07	-2.78 ± 0.20	0.82 ± 0.07	2.25 ± 0.20	0.65
E-Im ($f_{\text{ap}} < 1.5$)*	75	48	1.00 ± 0.14	-2.77 ± 0.38	0.57 ± 0.10	1.53 ± 0.31	0.56
Sb-Sc ($T = 3-5$)	88	30	0.88 ± 0.07	-2.82 ± 0.21	0.84 ± 0.08	2.39 ± 0.22	0.71

Notes. The entries are: Column 1: subsample considered. Column 2: total number of galaxies in the respective samples. Column 3: number of galaxies with upper limits in M_{H_2} and/or L_{FIR} . Column 4: bisector slope and its error of the best-fit regression line derived with the Schmitt binning method in the ASURV package. The slope and intercept are defined as $\log(A) = \text{intercept} + \log(B) \times \text{slope}$, where A is M_{H_2} or Σ_{H_2} and B is L_{B} , L_{K} , L_{FIR} , $(D_{25})^2$ or Σ_{SFR} , respectively. Column 5: bisector intercept and its error. Column 6 and 7: slope and intercept and their errors of the best-fit regression line derived with the Schmitt binning method in the ASURV package adopting L_{B} , L_{FIR} , L_{K} , D_{25}^2 or Σ_{SFR} as independent variable. Column 8: spearman's rho correlation coefficient, calculated with ASURV. (*) Only galaxies for which the aperture correction factor, f_{ap} (see Sect. 3.5.1), is less than 1.5.

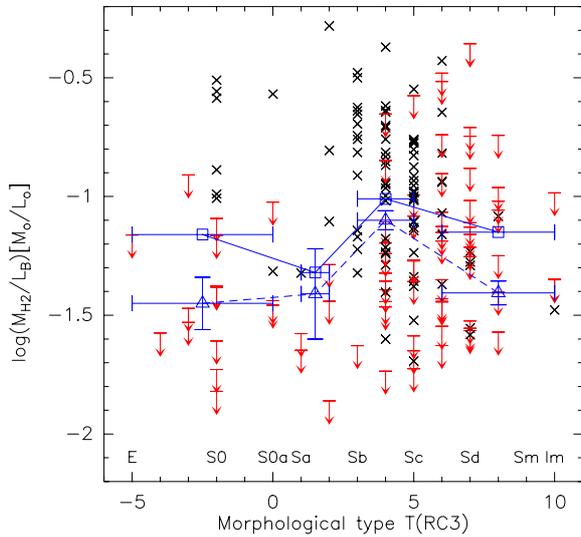


Fig. 7. The ratio between L_{B} and M_{H_2} as a function of morphological type. Triangles denote the mean value and its error for a range of morphological types and squares denote the median values, as listed in Table 6. The error bars in the x-direction denote the range of morphological types over which the mean and median have been taken.

The ratio is highest for galaxies of type $T = 3-5$. It is however remarkable that galaxies of type S0 and S0a with detections in CO have much higher values of $M_{\text{H}_2}/L_{\text{B}}$, in the range of spiral galaxies of type $T = 3-5$, than early-type galaxies with nondetection in CO.

In order to check whether the extrapolation of the molecular gas mass to the entire disk has introduced any biases, we show in Fig. 8 the relation between M_{H_2} and L_{B} only for galaxies

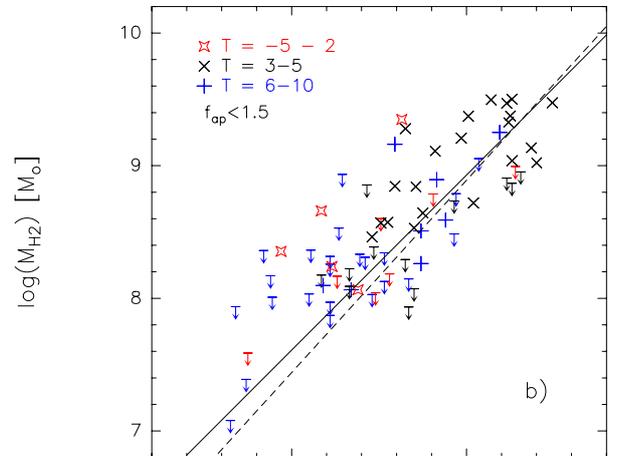


Fig. 8. M_{H_2} vs. L_{B} for galaxies in the redshift-limited CO sample with an aperture correction factor of less than $f_{\text{ap}} < 1.5$ ($n = 78$). The solid line is the best fit bisector line derived with ASURV for this restricted sample, and the dashed lines gives, for comparison, the fit for the entire redshift-limited CO sample.

with $f_{\text{ap}} < 1.5$. No significant difference compared to the entire redshift-limited CO sample can be seen, and the best-fit regression coefficients are the same within the errors (Table 7). We found this good agreement between entire redshift-limited CO sample and the subsample of galaxies with $f_{\text{ap}} < 1.5$ for all correlations studied. Therefore, in the following subsections we do not show the $f_{\text{ap}} < 1.5$ correlation separately, but we list in Tables 6 and 7 the mean values and the regression coefficients for this subsample.

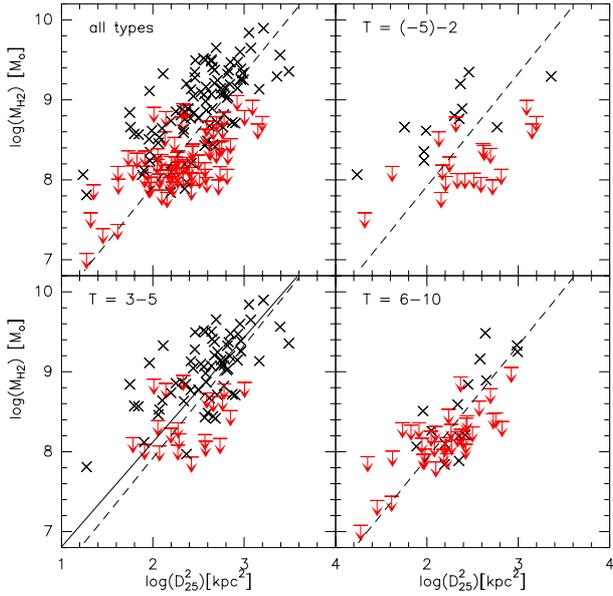


Fig. 9. M_{H_2} vs. square of the optical isophotal diameter, D_{25}^2 , for the redshift-limited CO sample ($n = 173$), including all morphological types, and for groups of different morphological types. The dashed line gives the best fit bisector (derived with ASURV) for all morphological types and the solid line is the best fit for the $T = 3-5$ sample (see Table 7).

4.2.2. Optical isophotal diameter

Figure 9 shows the relation between M_{H_2} and D_{25}^2 , for the entire redshift-limited sample and for subsamples of different morphological types, together with the best-fit bisector regression lines. For early-type galaxies ($T \leq 0$) only a very poor correlation is visible, whereas galaxies of type $T = 6-10$ seem to follow the same correlation as those of type $T = 3-5$.

The correlation between M_{H_2} and D_{25}^2 , has the lowest correlation coefficient ($r \sim 0.5$) among those considered in this paper (Table 7). Although the bisector slope is formally larger than 1, we do not find a variation of M_{H_2}/D_{25}^2 with increasing optical diameter. This shows that for this poor correlation the regression slope has to be taken with caution.

Figure 10 shows the ratio M_{H_2}/D_{25}^2 as a function of morphological type. The values are listed in Table 6. The ratio is highest for spiral galaxies of type $T = 3-5$. Similarly to $M_{\text{H}_2}/L_{\text{B}}$, S0 and S0a galaxies with detections in CO have high values of M_{H_2}/D_{25}^2 , similar to those of spiral galaxies of type $T = 3-5$, whereas M_{H_2}/D_{25}^2 of the nondetections is much lower.

4.2.3. Luminosity in the K-band

Figure 11 shows the relation between M_{H_2} and L_{K} , for the entire redshift-limited sample and for subsamples of different morphological types, together with the the best-fit bisector regression lines. The relation is close to linear. The correlation is very good ($r = 0.73$) for spiral galaxies of type $T = 3-5$. The distribution of the emission from spiral galaxies of later types ($T = 6-10$) is consistent with this correlation. However, early-type galaxies ($T \leq 0$) show a very poor correlation. Only the objects with CO detections follow the same correlation as spiral galaxies whereas most galaxies with CO nondetections have upper limits for M_{H_2} that lie considerably below it.

The ratio $M_{\text{H}_2}/L_{\text{K}}$ is shown in Fig. 12. It is lowest for early-type galaxies (up to $T = 2$), and increases for later types

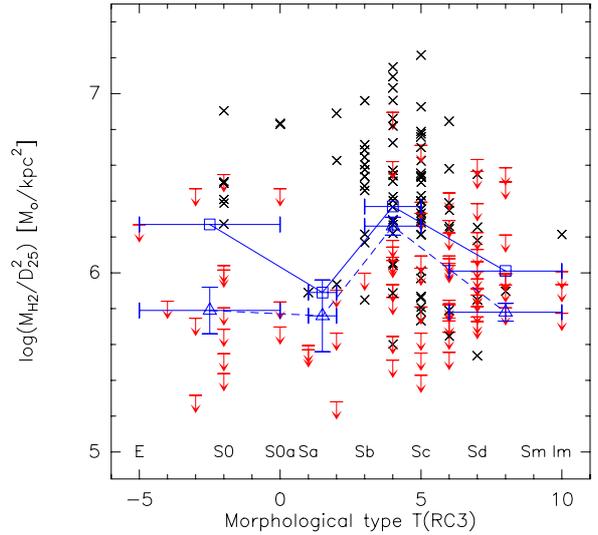


Fig. 10. The ratio between M_{H_2} and D_{25}^2 for the redshift-limited sample as a function of morphological type. Triangles denote the mean value and its error for a range of morphological types and squares the median values, as listed in Table 6. The error bars in the x -direction show the range of morphological types over which the mean and median have been taken.

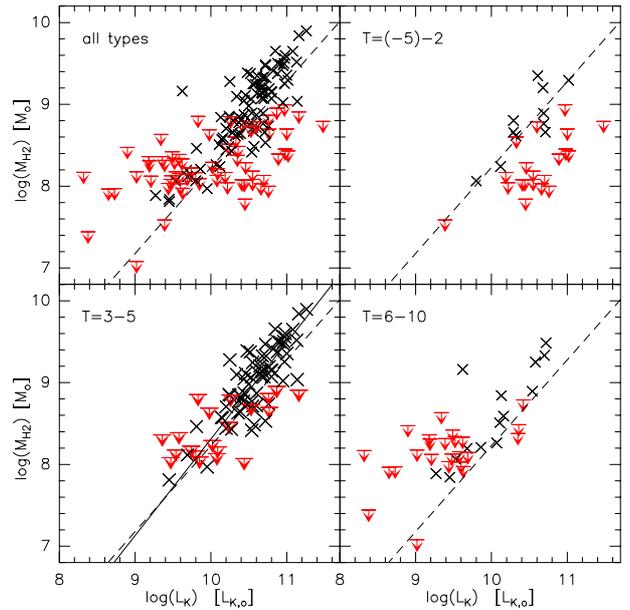


Fig. 11. The relation between M_{H_2} and L_{K} for the redshift-limited CO sample ($n = 173$), including all morphological types, and for groups of different morphological types. The dashed line gives the best fit bisector (derived with ASURV) for all morphological types and the solid line is the best fit for the $T = 3-5$ sample (see Table 7).

by a factor 3–5. From $T = 3$ on, the ratio is approximately constant and does not show the decrease it shows for $M_{\text{H}_2}/L_{\text{B}}$ and M_{H_2}/D_{25}^2 . Early-type (E+S0s) galaxies have a lower mean molecular gas mass per L_{K} than spiral galaxies. This is caused by galaxies not detected in CO, whereas, as seen before, S0 and S0a detected in CO have higher values of $M_{\text{H}_2}/L_{\text{K}}$, in the same range as spiral galaxies.

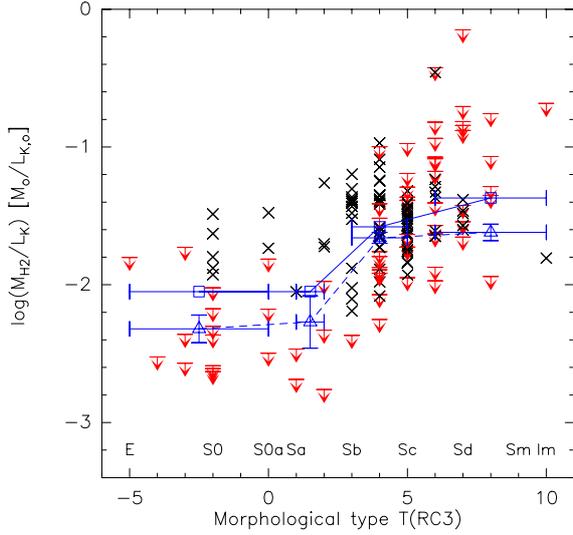


Fig. 12. The ratio between M_{H_2} and L_K as a function of morphological type. Triangles denote the mean value and its error for a range of morphological types and squares denote the median values, calculated treating upper limits as detections, as listed in Table 6. The error bars in the x -direction denote the range of morphological types over which the mean and median have been taken.

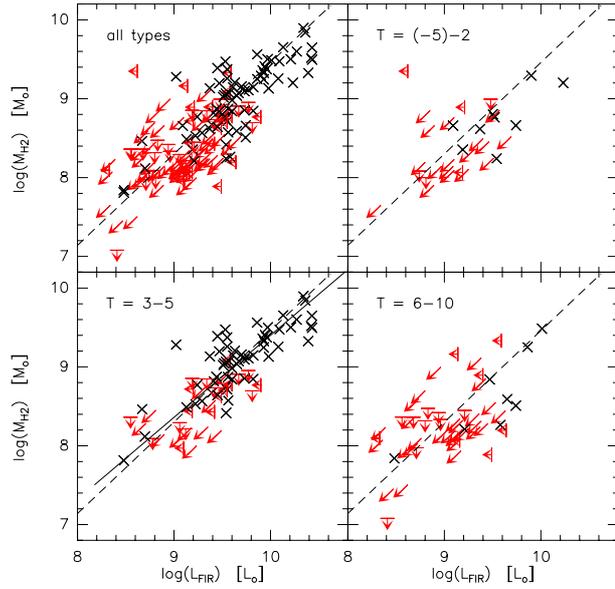


Fig. 13. M_{H_2} vs. L_{FIR} for the redshift-limited CO sample ($n = 173$), including all morphological types, and for groups of different morphological types. The dashed line gives the best fit bisector (derived with ASURV) for all morphological types and the solid line is the best fit for the $T = 3-5$ sample (see Table 7).

4.2.4. FIR luminosity, SF rate and efficiency

A good correlation is known to exist between M_{H_2} and L_{FIR} (e.g. Young & Scoville 1991) because both quantities are directly related to SF: the molecular gas as the fuel for SF and L_{FIR} as a tracer for SF based on the heating of the dust by newly born stars. Figure 13 shows the relation between M_{H_2} and L_{FIR} , for the entire redshift-limited sample and for subsamples of different morphological types, together with the best-fit bisector regression lines. We find a good correlations with a roughly linear slope (Table 7). For early ($T \leq 0$) and late ($T = 6-10$) type

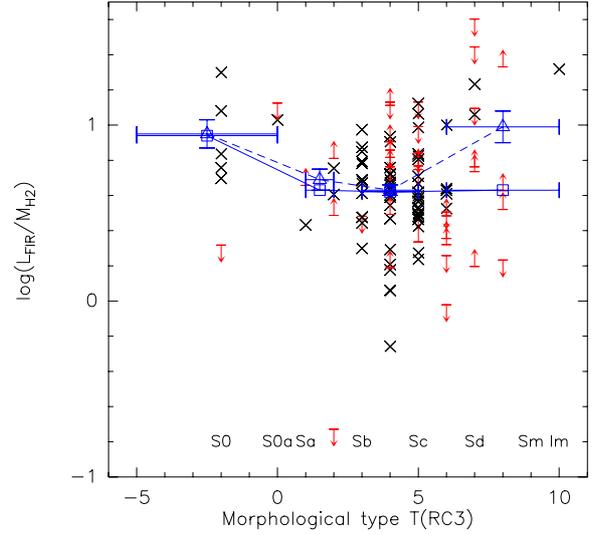


Fig. 14. The ratio between L_{FIR} and M_{H_2} as a function of morphological type. Galaxies with upper limits at both wavelengths are excluded. Triangles denote the mean value and its error for a range of morphological types and square signs denote the median values, as listed in Table 6. The error bars in the x -direction show the range of morphological types over which the mean and median have been taken.

galaxies, the distribution of M_{H_2} vs. L_{FIR} is consistent with the correlation found for galaxies of type $T = 3-5$.

Figure 14 shows the ratio $L_{\text{FIR}}/M_{\text{H}_2}$ as a function of morphological type. Early-type galaxies have a higher value, possibly due to a large fraction of their FIR emission not being heated by young stars but by the general interstellar radiation field. For late-type spirals ($T \geq 6$) the mean ratio increases again, but the low number of values and detections make any firm conclusion difficult.

These values and trends for $L_{\text{FIR}}/M_{\text{H}_2}$ are consistent with earlier results of Young et al. (1996) who studied them in a sample of 120 galaxies included in the FCRAO survey. They used a higher value of $N(\text{H}_2)/I_{\text{CO}} = 2.8 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$, but also define the FIR luminosity in the range between $1-500 \mu\text{m}$ which is, according to their prescription, between $\sim 0.1-0.2$ dex higher. Since both differences roughly compensate, their values of $L_{\text{IR}}/M_{\text{H}_2}$ are comparable to our values $L_{\text{FIR}}/M_{\text{H}_2}$. They find very similar values of $L_{\text{FIR}}/M_{\text{H}_2}$ for different morphological types as we do. They obtain value between 0.55 ± 0.08 and 0.61 ± 0.06 for morphological types $T = 3-5$ ($n = 45$), higher values (between 0.70 ± 0.13 and 1.53 ± 0.24) for later type galaxies ($T = 6-10$, $n = 19$), and, for earlier spiral types ($T = 1-2$, $n = 14$), mean values (0.65 ± 0.20 and 0.53 ± 0.09) that are similar to galaxies of type $T = 3-5$. Their sample only includes three galaxies of type S0-S0a and no elliptical galaxies, so that we cannot compare earlier types.

L_{FIR} is a good tracer for the star formation rate (SFR) due to two reasons: (i) young stars are formed in dense regions where dust opacities are high and (ii) the dust extinction curve peaks in the ultraviolet so that the radiation from young, massive stars is preferentially absorbed. Therefore, L_{FIR} as a good SFR tracer especially for actively SF galaxies. It has to be used with some caution in galaxies with a low SFR where dust heated from old stars can contribute to L_{FIR} , or in galaxies with a low metallicity and thus a low dust opacity (e.g. Bell 2003).

Keeping these limitations in mind, we use the formula of Kennicutt (1998) to calculate the SFR:

$$\text{SFR}(M_{\odot} \text{ yr}^{-1}) = 4.5 \times 10^{-44} L_{\text{IR}} (\text{erg yr}^{-1}), \quad (6)$$

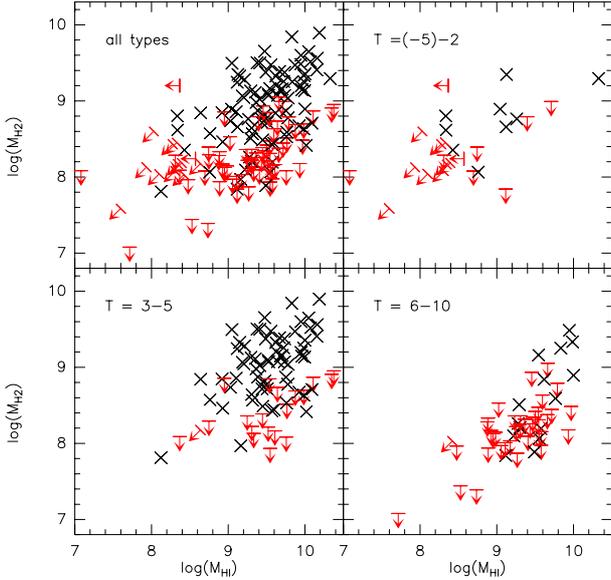


Fig. 15. The relation between M_{H_2} and M_{HI} for groups of different morphological types.

where L_{IR} is the total FIR luminosity in the range 8–1000 μm . This formula assumes a Salpeter Initial Mass Function. We convert this to a value based on the Kroupa (2001) IMF by dividing by a factor 1.59 (Leroy et al. 2008). In our analysis we use L_{FIR} , calculated following the formula given by Helou et al. (1988), which estimates the FIR emission in the wavelength range of 42–122.5 μm . We estimate L_{IR} from L_{FIR} using the result of Bell (2003) that on average $L_{\text{IR}} \sim 2 \times L_{\text{FIR}}$ for a heterogeneous sample of normal and starbursting galaxies. Adopting this factor and the conversion to the Kroupa IMF we calculate the SFR from the L_{FIR} as:

$$\begin{aligned} SFR(M_{\odot} \text{ yr}^{-1}) &= 4.5 \times 2 \times \frac{1}{1.59} 10^{-44} L_{\text{FIR}}(\text{erg yr}^{-1}) \\ &= 2.2 \times 10^{-10} L_{\text{FIR}}(L_{\odot}). \end{aligned} \quad (7)$$

We derive an average SFR for galaxies of type $T = 3-5$ of $\sim 0.7 M_{\odot} \text{ yr}^{-1}$. The ratio $L_{\text{FIR}}/M_{\text{H}_2}$ is proportional to the star formation efficiency (SFE), defined here as the ratio between SFR and M_{H_2} . The mean value of the SFE for galaxies of type $T = 3-5$ is 10^{-9} yr^{-1} (Table 6).

4.2.5. Atomic gas mass

Figure 15 shows the relation between M_{H_2} and M_{HI} for different groups of morphological types. The correlation with M_{HI} is much poorer than the other correlations considered here, with a Spearman correlation coefficients of $r = 0.44, 0.44, 0.29, 0.57$ for the entire redshift-limited sample, $T = (-5)-2$, $T = 3-5$ and $T = 6-10$, respectively. In most galaxies M_{HI} is higher than M_{H_2} . Some differences can be seen for the different morphological types: Early type galaxies ($T = -5-2$) have a high number of upper limits in both M_{H_2} and M_{HI} . The upper limits mainly populate the low M_{HI} and M_{H_2} part of the diagram, whereas the detections have values of M_{H_2} and M_{HI} comparable to those of spiral galaxies. Late-type galaxies ($T = 6-10$) are shifted towards higher M_{HI} ($\gtrsim 10^9 M_{\odot}$) but lower ($\lesssim 10^9 M_{\odot}$) M_{H_2} with a large number of upper limits in the latter. Galaxies of morphological types $T = 3-5$ have both high atomic gas and molecular gas masses ($\gtrsim 10^9 M_{\odot}$) with a low number of upper limits in M_{H_2} and almost none in M_{HI} .

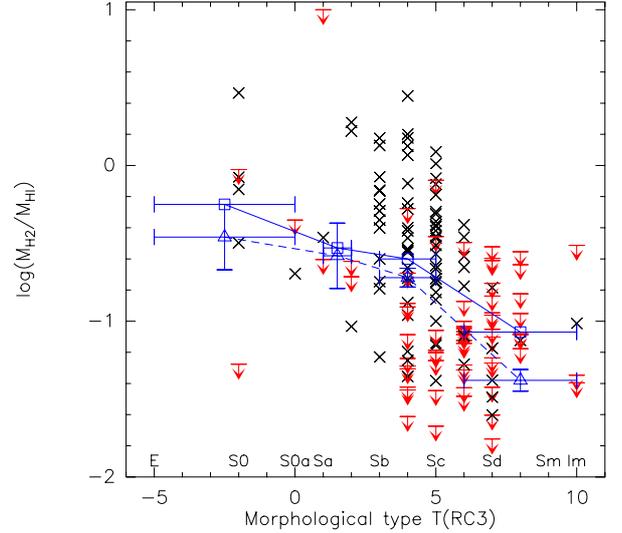


Fig. 16. The $M_{\text{H}_2}/M_{\text{HI}}$ ratio as a function of the morphological type. Triangles denote the mean value and its error for a range of morphological types and squares denote the median values, as listed in Table 6. The error bars in the x -direction denote the range of morphological types over which the mean and median have been taken.

Figure 16 displays the ratio $M_{\text{H}_2}/M_{\text{HI}}$ as a function of morphological type, showing a strong variation with T . The highest values are found for early-type galaxies, up to $T = 0$ (albeit with a high uncertainty due to the high number of upper limits). For later types, $M_{\text{H}_2}/M_{\text{HI}}$ is decreasing strongly. The mean ratio $M_{\text{H}_2}/M_{\text{HI}}$ is significantly lower than 1 for all morphological types.

4.3. Expected molecular gas content in a galaxy

We showed in Sect. 4.2 that good correlations exist between M_{H_2} and other parameters of a galaxy (L_{B} , L_{K} and L_{FIR}) and a somewhat poorer correlation with D_{25}^2 . In Table 7 we list, apart from the linear regression parameters, also the Spearman's rho correlation coefficient and in Table 6 the different ratios depending on the morphological types. All these relations can be used to study differences in the molecular gas content of other sample, like e.g. interacting galaxies, with respect to isolated galaxies.

The best correlation exists between M_{H_2} and L_{FIR} ($r \geq 0.8$). L_{FIR} is thus a very reliable way for predicting the expected molecular gas content in a galaxy. However, L_{FIR} might not be a good parameter when searching for variations of M_{H_2} in interacting galaxies because L_{FIR} itself, tracing the SFR , is easily affected in such an environment. A very good, and roughly linear, correlation also exists between M_{H_2} and L_{K} for galaxies of type $T = 3-5$ ($r = 0.73$). The luminosity in the K -band as a measure of the total stellar mass is less affected by recent events than L_{FIR} or L_{B} and thus a good normalization parameter when searching for changes in M_{H_2} . This correlation is, however, poor for early type galaxies ($T \leq 2$), where the undetected objects have ratios $M_{\text{H}_2}/L_{\text{K}}$ well below the values for spiral galaxies with $T \geq 3$ (see Fig. 11 and Table 6) so that for those types L_{K} is not recommended as a measure of the expected M_{H_2} . There is also a good correlation between M_{H_2} and L_{B} ($r \sim 0.65$). The ratio $M_{\text{H}_2}/L_{\text{B}}$ is however not constant, but increases with L_{B} which has to be taken into account in any comparison. Finally, the poorest correlation ($r \sim 0.5$) exists with the isophotal diameter which is not a very reliable parameter for predicting M_{H_2} .

Apart from using the ratio of M_{H_2} to another parameter, we can use the correlations, defined by the linear regression parameters listed in Table 7, for predicting the expected M_{H_2} and determine whether a deficiency or an excess of M_{H_2} exists in an object in comparison to isolated galaxies.

We define the deficiency in M_{H_2} in an analogous way to the definition in M_{HI} of Haynes & Giovanelli (e.g. 1984):

$$\text{Def}(M_{\text{H}_2}) = \log(M_{\text{H}_2, \text{predicted}}) - \log(M_{\text{H}_2, \text{observed}}). \quad (8)$$

Note that in this definition, a positive value of $\text{Def}(M_{\text{H}_2})$ means a deficiency and a negative value means an excess. We can derive the predicted M_{H_2} , $M_{\text{H}_2, \text{predicted}}$, from any of the parameters, X , (L_{B} , D_{25}^2 , L_{K} or L_{FIR}) as:

$$\log(M_{\text{H}_2, \text{predicted}}) = \text{intercept} + \text{slope} \times \log(X), \quad (9)$$

where *intercept* and *slope* are the parameters of the best fit listed in Table 7. These definitions allow us to directly take the effect of a nonlinearity of a correlation into account.

In Table 7 we have given the values for two types of regressions: the bisector fit and the fit obtained by taking M_{H_2} as the dependent variable, $O(Y|X)$, and minimizing the distance of the M_{H_2} measurements from the best-fit regression line. The regression parameters are different for both methods because of the scatter in the data and the difference is larger for poorer correlations. The $O(Y|X)$ fit is the appropriate regression for predicting M_{H_2} from L_{B} , whereas the bisector regression is the best estimate for the underlying correlation between two parameters (Isobe et al. 1990). For a sample covering the same luminosity range, $O(Y|X)$ is the best way for predicting the expected M_{H_2} . For samples with a different luminosity range, however, the bisector fit is better since it provides a more reliable extrapolation.

4.4. The Kennicutt-Schmidt law

We used our data to calculate the Kennicutt-Schmidt law, i.e. the relation between the disk-averaged gas column density and the disk-averaged SFR per area, Σ_{SFR} . Figure 17a shows the relation with the molecular gas column density, Σ_{H_2} , and Fig. 17b with the total (molecular+atomic) gas column density, $\Sigma_{\text{H}_2+\text{HI}}$. The surface densities were calculated by dividing the SFR , respectively the (extrapolated) molecular or total gas mass, by the galaxy surface $\pi D_{25}^2/4$. A clear correlation exists with the molecular gas, but none with the total gas, showing a lack of correlation with the atomic gas column density. Our findings are in agreement with previous results based on spatially resolved analysis (Wong & Blitz 2002; Bigiel et al. 2008; Verley et al. 2010), showing that the SFR is strongly related to molecular gas only. The best-fit regression yields $\Sigma_{SFR} \propto \Sigma_{\text{H}_2}^{0.89 \pm 0.07}$ (Table 7). This slope, close to unity, is again consistent with the results of Wong & Blitz (2002) and Bigiel et al. (2008) for a spatially resolved analysis.

5. Discussion

We compare our data to that of other samples of “normal” galaxies and also search for differences in samples of interacting galaxies. The samples of normal galaxies that we consider are made of not obviously interacting galaxies, which are however selected without a clear isolation criteria, and some of these samples contain, e.g. several cluster galaxies. In all these comparisons we have adjusted the molecular gas masses to our definition, i.e. same conversion factor and no consideration of the helium fraction.

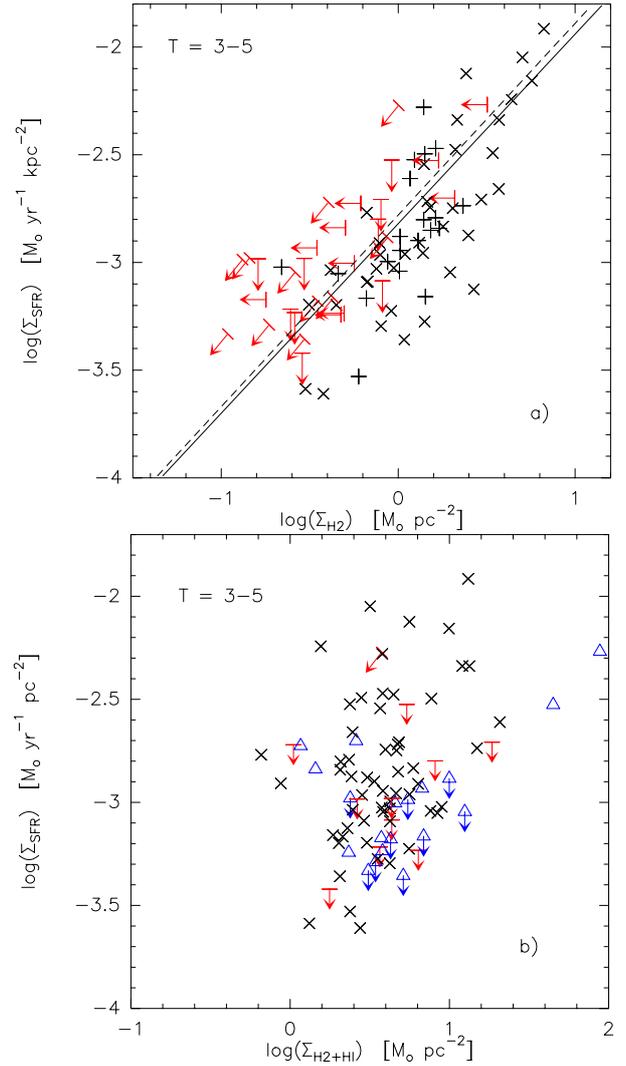


Fig. 17. Panel **a**) The relation between the surface density of the molecular gas and the SFR per area for morphological types $T = 3-5$, calculated by dividing the molecular gas mass and the SFR derived from L_{FIR} by the surface of the galaxies, $\pi(D_{25}/2)^2$. The full line shows the bisector best fit for this sample, and the dashed line the best fit to the sample of all morphological types. Panel **b**) The same relation with the total (atomic + molecular) gas surface density. The blue triangles show the galaxies with either an upper limit in HI or in CO. The gas surface density for these galaxies has a lower and an upper limit which for the galaxies in this figure are very close together (within the size of the triangle).

5.1. Comparison to studies of normal galaxies

5.1.1. Relation between molecular gas, FIR and blue luminosity

The nonlinear relation between M_{H_2} and L_{B} has been found by other groups as well (see Perea et al. 1997, and references therein), with similar slopes as found by us. Their study was based on a smaller number ($n = 68$) of galaxies selected with a less rigorous criterion with respect to the environment. They discussed the cause of the nonlinearity and conclude that the most likely reason is extinction affecting L_{B} and increasing with galaxy luminosity. They predicted that the relation between M_{H_2} and luminosities at longer wavelengths should be more linear. This prediction is confirmed by the nearly linear relation found between M_{H_2} and L_{K} in our analysis.

Table 8. Deficiencies of M_{H_2} , L_{FIR} and $L_{\text{FIR}}/M_{\text{H}_2}$ in interacting sample and AMIGA.

	AMIGA		Casasola et al. (2004)		Perea et al. (1997)	
	all types	$T = 3-5$	all types	$T = 3-5$	WPER	SPER
$\langle \text{def}(M_{\text{H}_2}) \rangle (L_{\text{B}}, \text{bise.})$	0.07 ± 0.04	0.07 ± 0.04	0.13 ± 0.07	-0.31 ± 0.07	-0.03 ± 0.07	-0.25 ± 0.08
n/n_{up}	173/79	88/21	153/35	68/9	43/0	35/0
$\langle \log(M_{\text{H}_2}/L_{\text{B}}) \rangle$ (for $10^{10} < L_{\text{B}} \leq 10^{10.6}$)	-1.10 ± 0.06	-1.04 ± 0.05	-1.12 ± 0.08	-0.71 ± 0.08	-0.93 ± 0.06	-0.71 ± 0.08
n/n_{up}	50/11	40/5	85/13	39/6	24/0	19/0
$\langle \text{def}(M_{\text{H}_2}) \rangle (L_{\text{K}}, \text{bise.})$	-0.14 ± 0.19	0.05 ± 0.04	0.03 ± 0.08	-0.16 ± 0.06	0.13 ± 0.07	-0.02 ± 0.05
$\langle \log(M_{\text{H}_2}/L_{\text{K}}) \rangle$	-1.87 ± 0.05	-1.66 ± 0.06	-1.70 ± 0.08	-1.37 ± 0.07	-1.65 ± 0.07	-1.47 ± 0.05
n/n_{up}	173/79	88/21	132/29	60/6	43/0	32/0
$\langle \text{def}(L_{\text{FIR}}) \rangle$	-0.02 ± 0.04	-0.05 ± 0.04	-0.39 ± 0.02	-0.44 ± 0.03	-0.48 ± 0.08	-1.07 ± 0.09
n/n_{up}	172/75	88/20	628/0	340/0	43/0	35/0
$\langle \log(L_{\text{FIR}}/M_{\text{H}_2}) \rangle$	0.72 ± 0.03	0.63 ± 0.03	0.89 ± 0.05	0.75 ± 0.05	0.98 ± 0.07	1.33 ± 0.05
n/n_{up}	97/22	68/10	105/15	51/4	43/0	35/0

We compared our mean value of $M_{\text{H}_2}/L_{\text{B}}$ for galaxies of type $T = 3-5$ to results for a large sample of normal galaxies, studied by [Bettoni et al. \(2003\)](#). They searched the literature for galaxies with data for their ISM properties, excluding galaxies with a known peculiarity (interacting, disturbed, galaxies with polar rings or counterrotation) and with active galactic nuclei. Their sample includes 177 galaxies of type $T = 3-5$ with CO(1-0) data (160 detections and 17 upper limits) with values of $\log(L_{\text{B}})$ between 9 and 11. They derive a mean value (adapted to our convention for the calculation of the M_{H_2} and L_{B}) of $M_{\text{H}_2}/L_{\text{B}} = -0.92 \pm 0.04$ for these galaxies. When restricting the range of L_{B} to $\log(L_{\text{B}}) = 10-10.6$, the mean value is -0.82 ± 0.05 , about 0.2 dex higher than the corresponding value for the AMIGA sample (see Table 8) showing that AMIGA galaxies have a lower molecular gas content. When comparing their values for M_{H_2}/D_{25}^2 a similar difference is found.

The relation between M_{H_2} and L_{FIR} in nonstarburst galaxies has been found to be close to linear in other studies (e.g. [Perea et al. 1997](#); [Gao & Solomon 2004](#)), in agreement with our results.

5.1.2. Gas depletion time

We derived in Sect. 4.2.4 the SFE (defined as the SFR/M_{H_2}). The SFE is directly related to the molecular gas depletion time, τ_{dep} , by $\tau_{\text{dep}} = \text{SFE}^{-1}$. The gas depletion time for our sample has a mean value of $\log(\tau_{\text{dep}}) = 8.9$ yr for the entire redshift-limited sample and $\log(\tau_{\text{dep}}) = 9$ yr for galaxies of type $T = 3-5$ (see Table 6), with a spread of values roughly ranging between $\log(\tau_{\text{dep}}) = 8.5$ yr and $\log(\tau_{\text{dep}}) = 9.5$ yr (see Fig. 14).

This value can be compared to those found in recent surveys. [Bigiel et al. \(2011\)](#) derived a mean gas depletion time of 2.35 Gyr from spatially resolved observations of 30 nearby galaxies in the HERACLES survey. This value includes a helium fraction of a factor 1.36, thus giving $\tau_{\text{dep}} = 1.7$ Gyr without helium. They furthermore showed that this value is consistent with a wide range of molecular gas depletion times from the literature, albeit with a large standard deviation of 0.23 dex. This value is only slightly higher than our value for isolated galaxies. The small difference could be due to the fact that our value is global, and thus might encompass some FIR emission not directly associated to SF from the outskirts of the galaxies, whereas the value from [Bigiel et al. \(2011\)](#) is from a spatially resolved study.

[Saintonge et al. \(2011\)](#) studied the molecular gas depletion time, τ_{dep} , for a volume limited sample of 222 galaxies with $0.025 < z < 0.05$ observed in the COLD GASS survey. They found values for the gas depletion time in the range of roughly

$\log(\tau_{\text{dep}}) = 8.6$ yr and 9.5 yr, with a mean value of $\tau_{\text{dep}} = 1$ Gyr (for a [Chabrier \(2003\)](#) IMF which gives a mass comparable to within $\sim 10\%$ to the Kroupa IMF). Both the range and the mean agree very well with our values.

They furthermore found a good correlation of τ_{dep} with M_* and with the specific SFR , $sSFR = SFR/M_*$. We tested both correlations with our data. We did not find a similarly good correlation with L_{K} (which is in a good approximation proportional to the stellar mass M_*) although our sample covered a similar range of stellar masses, up to several $10^{11} M_{\odot}$. Taking into account all morphological types, we found evidence for a weak trend (correlation coefficient $r = 0.25$) which completely disappeared when restricting the sample to $T = 3-5$ ($r = 0.08$).

We could confirm with our data the existence of a correlation between τ_{dep} and $sSFR$. This correlation is however expected because both τ_{dep} and the $sSFR$ depend on the SFR , and L_{K} and M_{H_2} show a good correlation. Thus, the respective ratios are expected to correlate.

5.1.3. The molecular-to-atomic gas ratio

The value of $M_{\text{H}_2}/M_{\text{HI}}$ in galaxies as a function of morphological type has been controversial. In a large survey of spiral galaxies, [Young et al. \(1995\)](#) mapped a sample of about 300 galaxies with the FCRAO telescope. [Young & Knezek \(1989\)](#) studied the dependence of M_{H_2} on M_{HI} for that sample. They derived a continuous decrease of $M_{\text{H}_2}/M_{\text{HI}}$ from early to late-type galaxies with mean values above 1 for early types. [Casoli et al. \(1998\)](#) studied the molecular gas properties of a large ($n = 528$), heterogeneous sample of galaxies, composed of data from the literature and their own observations. Their data consisted both of mapped galaxies and of objects where only the central position had been observed. In agreement with [Young et al. \(1995\)](#), they found a decrease in $M_{\text{H}_2}/M_{\text{HI}}$ from early to late-type galaxies, but obtained much lower values for $M_{\text{H}_2}/M_{\text{HI}}$, especially for early-type spirals. In Fig. 18 we compare our results to these two studies and furthermore to the THINGS sample ([Leroy et al. 2008](#)) and the Nobeyama survey ([Nishiyama & Nakai 2001](#)). [Bettoni et al. \(2003\)](#) (not included in Fig. 18) provide values for a sample of 427 normal galaxies in agreement with [Casoli et al. \(1998\)](#) for $T > 0$ and higher values (by 0.5-1 dex) for $T \leq 0$.

The data from all studies show a decrease of the $M_{\text{H}_2}/M_{\text{HI}}$ gas mass ratio towards late morphological types. A pronounced step in the ratio takes place at $T \sim 6$. The low values found for late-type galaxies could be due to two effects: (i) late-type galaxies are richer in HI ([Haynes & Giovanelli 1984](#)) or (ii) they have a lower molecular gas content. A comparison of M_{HI} and M_{H_2} to the blue luminosity or the optical diameter shows that

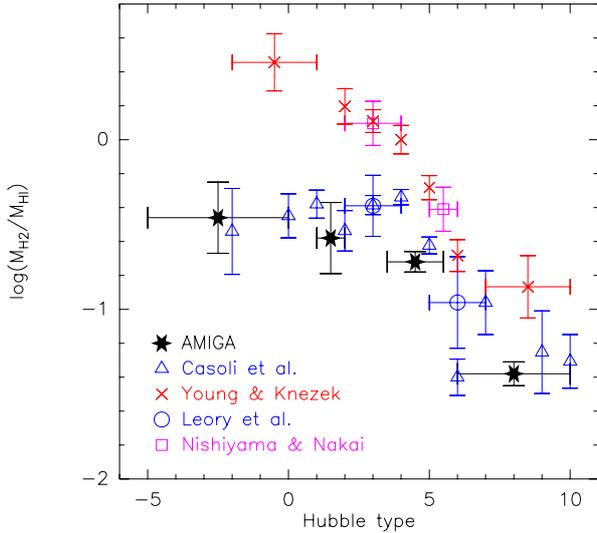


Fig. 18. Comparison of our values for $M_{\text{H}_2}/M_{\text{HI}}$ (black stars) to those from the literature: Casoli et al. (1998) (blue triangles), Young & Knezek (1989) (red crosses), Leroy et al. (2008) (blue circles) and Nishiyama & Nakai (2001) (magenta squares). The molecular gas mass have all been adapted to a common conversion factor of $2 \times 10^{20} \text{ cm}^{-2}$ and no consideration of the helium mass.

both effects take place: the ratio $M_{\text{HI}}/L_{\text{B}}$ (respectively M_{HI}/D_{25}^2) increases for types $T \geq 6$ by ~ 0.2 – 0.3 dex whereas $M_{\text{H}_2}/L_{\text{B}}$ (respectively M_{H_2}/D_{25}^2) decreases by ~ 0.3 – 0.5 dex (Young & Knezek 1989; Casoli et al. 1998; Bettoni et al. 2003). Our data show the same behaviour. The strong decrease of $M_{\text{H}_2}/L_{\text{B}}$ and M_{H_2}/D_{25}^2 could be due to a real decrease in the molecular gas mass or due to the fact that late-type galaxies tend to have lower metallicities so that we probably underestimate the true M_{H_2} by using the Galactic conversion factor.

Although the general trends in the data sets are the same, with a pronounced and continuous decrease of $M_{\text{H}_2}/M_{\text{HI}}$ from early to late-type galaxies, there are considerable differences between the different samples (see Fig. 18). The differences are up to an order of magnitude for elliptical, lenticular and early-type spiral galaxies (up to $T \sim 3$), and less (up to 0.4 dex) for later type spirals. There is in general a good agreement between the values found by Casoli et al. and ours, the match being very good for early-type galaxies (up to $T = 0$) whereas for later-type galaxies our values lie somewhat below. The results from the THINGS survey (Leroy et al. 2008) are also in agreement with the data of Casoli et al., and only slightly higher than our values. The results by Young & Knezek (1989) and Nishiyama & Nakai (2001) give much higher values than the other surveys. This could be due to the sample selection. In the sample of Young & Knezek (1989) FIR or optically bright galaxies were selected, so that a high CO emission can be expected. Furthermore, the Young & Knezek (1989) survey contains objects from the Virgo Cluster, and cluster galaxies are known to be HI deficient on average. Cluster galaxies were excluded in Casoli et al., and are not present in our sample either. A selection effect can also account for the difference between the samples of Nishiyama & Nakai, Leroy et al. and our data. The samples differ in the mean $L_{\text{FIR}}/L_{\text{B}}$ with the Nishiyama & Nakai sample being the FIR brightest with a mean $\log(L_{\text{FIR}}/L_{\text{B}}) = 0.10 \pm 0.07$ whereas the Leroy et al. and our sample show lower values ($\log(L_{\text{FIR}}/L_{\text{B}}) = -0.51 \pm 0.06$, respectively $\log(L_{\text{FIR}}/L_{\text{B}}) = -0.49 \pm 0.03$). Since galaxies with a higher $\log(L_{\text{FIR}}/L_{\text{B}})$ tend to have a higher $M_{\text{H}_2}/M_{\text{HI}}$, the observed trend is understandable.

A noticeable point is that the mean $M_{\text{H}_2}/M_{\text{HI}}$ of the AMIGA sample represents for all morphological types the lower limit of all samples. For late-types, the AMIGA galaxies have the lowest $M_{\text{H}_2}/M_{\text{HI}}$, even though the M_{H_2} is extrapolated unlike other studies that are usually based on a central pointing only. This is in line with the low molecular gas content that we found in comparison to the sample of Bettoni et al. (2003).

5.2. Comparison to studies of interacting galaxies

5.2.1. Is the molecular gas content enhanced in interacting galaxies?

Several studies in the past have concluded that M_{H_2} in interacting galaxies is enhanced (Braine & Combes 1993; Casasola et al. 2004; Combes et al. 1994), based on a higher value of $M_{\text{H}_2}/L_{\text{B}}$ or M_{H_2}/D_{25}^2 compared to noninteracting galaxies. However, we found that the ratio $M_{\text{H}_2}/L_{\text{B}}$ increases with L_{B} and this trend has to be taken into account when comparing isolated and interacting samples. Indeed, Perea et al. (1997) found no difference in the correlation between M_{H_2} and L_{B} for samples of isolated, strongly and weakly perturbed galaxies.

We use the sample of Casasola et al. (2004) of interacting galaxies to search for a possible excess in M_{H_2} with respect to AMIGA galaxies. Their sample includes 153 galaxies with molecular gas data from different sources. Casasola et al. found that the mean ratio of $M_{\text{H}_2}/L_{\text{B}}$ for spiral galaxies was, depending on the morphological type, between about 0.2 and 1.0 dex higher than for a sample of 427 noninteracting galaxies from Bettoni et al. (2003) and concluded that M_{H_2} was enhanced in interacting galaxies. However, since their sample of interacting galaxies is on average 0.5 mag brighter, a higher $M_{\text{H}_2}/L_{\text{B}}$ is already expected due to the higher luminosity. We furthermore include the samples of strongly and weakly perturbed galaxies from Perea et al. (1997) in this test. The weakly perturbed sample has 43 galaxies and includes classes 1, 2, and 3 of Solomon & Sage (1988) and class 2 objects from the luminous IRAS sample of Sanders et al. (1991). The strongly perturbed sample has 35 galaxies and includes interaction class 4 of Solomon & Sage (1988), interaction classes 3 and 4 of Sanders et al. (1991) and closely interacting pairs from Combes et al. (1994).

We searched for a possible enhancement of M_{H_2} in comparison to L_{B} and to L_{K} in these samples, both by applying the deficiency parameter and by comparing the ratios. The mean values are listed in Table 8. We note that the interacting samples are more luminous (by about 0.5 dex) in both L_{B} and L_{K} than the AMIGA sample so that we have to extrapolate the relations found for the AMIGA galaxies to higher luminosities. For the calculation of the deficiency parameter we therefore use the bisector fit as the best fitting method for extrapolations. We use the fits for the AMIGA $T = 3$ – 5 subsample to compare to the weakly and strongly perturbed samples WPER and SPER, since spiral galaxies are the better comparison for these actively star-forming objects. For the Casasola et al. sample information about the morphological types are available and we are able to do the analysis both for the entire sample and for $T = 3$ – 5 , using the values for the corresponding morphological types in AMIGA. When comparing the ratio $M_{\text{H}_2}/L_{\text{B}}$ we restrict the galaxies that we consider to the same range of L_{B} in order to avoid effects caused by the nonlinearity in the correlation. For the roughly linear $M_{\text{H}_2}/L_{\text{K}}$ ratio this is not necessary (we checked that no difference in $M_{\text{H}_2}/L_{\text{K}}$ was present for low and high L_{K} in the AMIGA sample).

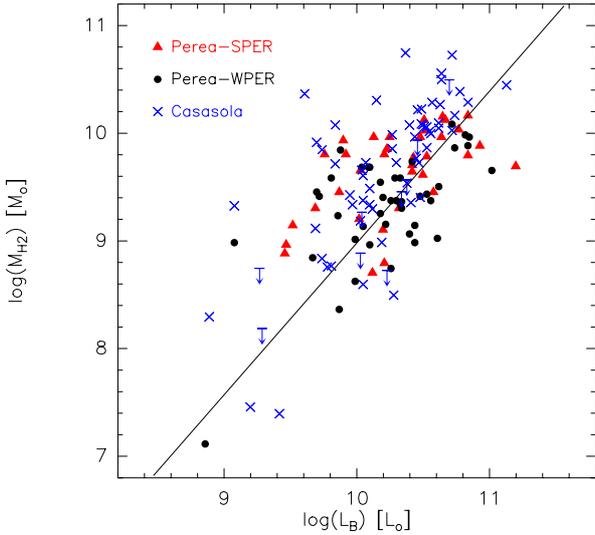


Fig. 19. The molecular gas mass vs. L_B for different sample of interacting galaxies: Galaxies of type $T = 3-5$ from the sample of Casasola et al. (2004) and a sample of weakly (WPER) and strongly (SPER) perturbed galaxies from Perea et al. (1997). We adapted both the molecular gas masses and L_B to our definition. The full line is the regression fit obtained for the AMIGA $T = 3-5$ sample from Table 7.

Figure 19 shows M_{H_2} vs. L_B for the three samples compared to the bisector fit of the AMIGA $T = 3-5$ sample. An excess of M_{H_2} is visible for both the Casasola $T = 3-5$ and SPER sample. This is confirmed by the mean value of the deficiency (Table 8), both for the Casasola et al. $T = 3-5$ and the SPER sample a clear excess (i.e. a negative value of the deficiency) of M_{H_2} is found. This excess in the SPER sample was not found in Perea et al. (1997) due to the different regression line they used. For the WPER sample, on the other hand, no deficiency nor excess is found. When comparing the ratio M_{H_2}/L_B we confirm the higher values for both the Casasola and the SPER sample, with mean values of about 0.3 dex higher than for the AMIGA $T = 3-5$ sample. The value of M_{H_2}/L_B for the WPER sample is compatible with AMIGA within the errors. The entire (i.e. all morphological types) Casasola et al. sample has a value of M_{H_2}/L_B compatible with AMIGA, showing the importance of taking the morphological type into account.

When doing a similar analysis based on L_K (see Fig. 20), we find again no indications for an enhancement in M_{H_2} for the WPER sample nor for the total Casasola sample, neither from the deficiency nor from the ratio. There is a clear excess in M_{H_2} for galaxies of type $T = 3-5$ from the Casasola sample, quantified both in the ratio, which is about 0.3 dex higher for $T = 3-5$ AMIGA galaxies, and in the deficiency parameter. Also the SPER sample shows a higher M_{H_2}/L_K ratio than the AMIGA sample, however, no indication of an M_{H_2} excess from the deficiency parameter. The discrepancy between the two indicators (mean and deficiency) is probably due to the small sample size and the small amount of the molecular gas excess. We suggest to rely in this case on M_{H_2}/L_K as the more robust indicator.

In summary, by comparing the molecular gas mass to L_K and L_B and using both the deficiency and the ratios M_{H_2}/L_K and M_{H_2}/L_B we found the clearest evidence for an enhancement of M_{H_2} in the Casasola sample of interacting galaxies of type $T = 3-5$, which is the largest comparison sample in our study. Evidence for an enhancement was also found for the Perea sample of strongly perturbed interacting galaxies (SPER). No evidence for any enhancement was found for the Perea sample

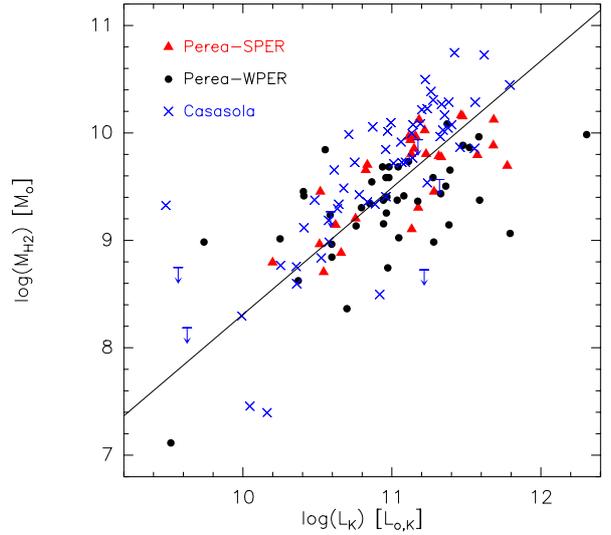


Fig. 20. The molecular gas mass (adapted to our conversion factor) vs. L_K for the same samples as in Fig. 19. The full line is the regression fit obtained for the AMIGA $T = 3-5$ sample from Table 7.

of weakly perturbed interacting sample (WPER). Based on the present data, it is not entirely clear where the differences between these samples come from. A possible reason could be a lower degree of interaction in the WPER sample. We would like to point out the importance of matching the luminosity range when comparing parameters with a nonlinear correlation, as M_{H_2}/L_B , and the importance of comparing the same morphological types, since there are generally large difference between early type and spiral galaxies, in particular for M_{H_2}/L_K .

What influence has the fact that the molecular gas masses in these samples are not aperture corrected as in the AMIGA sample? We do not expect this effect to be very important in interacting galaxies where the SF and thus the molecular gas usually tend to be more concentrated to the central regions. However, we can make an estimate of the importance of this effect for the Casasola et al. sample. The median angular diameter of the galaxies of type $T = 3-5$ in this sample is $90''$. If we assume that the galaxies were observed only at the central position with a beam size of $50''$ (the typical beam size of the radio telescopes used in surveys) the predicted aperture correction according to our prescription is between a factor of 1.2 and 1.4 (for edge-on and face-on galaxies, respectively). Thus, in this case the total molecular gas content would be 0.08–0.15 dex higher. Thus, if the molecular gas in the interacting galaxies of the Casasola sample are distributed in a similar way as in isolated galaxies, this difference would strengthen the finding that M_{H_2} is enhanced in this sample of interacting galaxies. It also shows the importance of mapping the molecular gas in galaxies in order to be able to compare different samples in a reliable way.

5.2.2. Is L_{fir} and the SFE enhanced in interacting galaxies?

We use the same samples as in the previous subsection to look for a possible enhancement of L_{FIR} in interacting galaxies. In Fig. 21 L_{FIR} is compared to the blue luminosity. We include the best-fit regression line found for the AMIGA $T = 3-5$ sample presented in Lisenfeld et al. (2007) (Table 6, $\log(L_{\text{FIR}}) = 1.35 \times \log(L_B) - 3.98$). We see a clear excess of L_{FIR} with respect to this regression line for the three samples, the strongest for the sample of strongly perturbed galaxies (SPER). The excess can

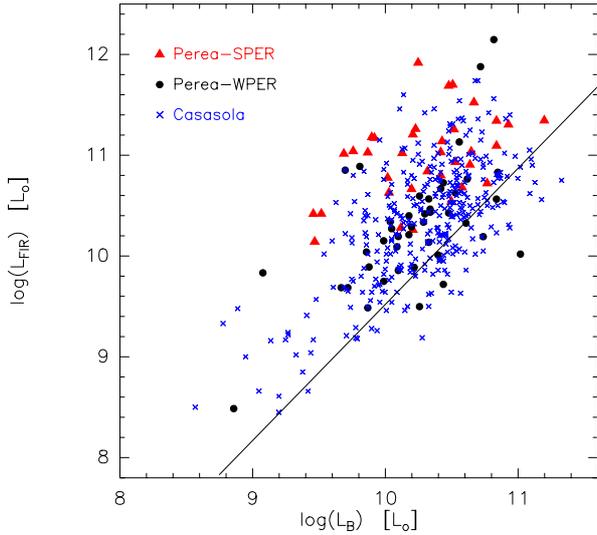


Fig. 21. The FIR luminosity vs. blue luminosity for different samples of interacting galaxies: Casasola et al. (2004) (only spiral galaxies with type $T = 3-5$ are shown, in order not to overload the plot), and a sample of weakly (WPER) and strongly (SPER) perturbed galaxies from Perea et al. (1997). The full line is the regression fit obtained for the AMIGA $T = 3-5$ sample from Lisenfeld et al. (2007).

be quantified by calculating the L_{FIR} deficiency, defined in an analogous way as the M_{H_2} deficiency. The values are listed in Table 8 and confirm the visual impressions of an excess in L_{FIR} of about an order of magnitude for the SPER sample.

The large excess in L_{FIR} together with a smaller (or no) excess in M_{H_2} results in a higher value of $\text{SFE} \propto L_{\text{FIR}}/M_{\text{H}_2}$ compared to the AMIGA sample for the strongly and weakly perturbed samples. Comparing these values to the results for the AMIGA sample we find an increase of about a factor 5 for the strongly perturbed sample and of about 2 for the weakly perturbed sample. The SFE in the Casasola sample is similar to the AMIGA sample.

For higher infrared luminosities, the value of $L_{\text{FIR}}/M_{\text{H}_2}$ is known to increase strongly. Sanders et al. (1991) studied the molecular gas content in luminous infrared galaxies, ranging from $L_{\text{IR}} = 10^{10} L_{\odot}$ to several $10^{12} L_{\odot}$, and showed that the ratio $L_{\text{IR}}/M_{\text{H}_2}$ increases strongly with IR luminosity and with the degree of interaction. Whereas for isolated, low-luminosity ($L_{\text{IR}} < 10^{11} L_{\odot}$) galaxies they found values of $L_{\text{IR}}/M_{\text{H}_2}$ similar to ours, $L_{\text{IR}}/M_{\text{H}_2}$ increases by a factor of about 10 for galaxies with $L_{\text{IR}} \sim 10^{12} L_{\odot}$ which are mostly advanced mergers. Similarly high values of $L_{\text{FIR}}/M_{\text{H}_2} \sim 50$ have been found by Solomon et al. (1997) for ULIRGs.

6. Conclusions and summary

We presented molecular gas masses, based on CO observations, for a sample of 273 isolated galaxies and we performed a statistical analysis for a redshift-limited sample of 173 isolated galaxies with recession velocities between 1500 and 5000 km s^{-1} . The observations covered in most cases only the central position of the galaxies. In order to correct for the missing molecular gas mass outside the observed area, we derived and applied an aperture correction assuming an exponentially decreasing CO disk. We obtained the following results:

1. We compared the molecular gas mass to different parameters (L_{B} , L_{K} , D_{25}^2 and L_{FIR}) in order to characterize the relations

followed by isolated galaxies and establish a baseline that can be used to find possible deviations for interacting galaxies. We concentrated our analysis on the morphological types $T = 3-5$ (Sb-Sc) which represents the bulk of our sample (51% of the galaxies are of these types) where also the detection rate of CO (74%) was highest.

2. We found good correlations with these parameters, roughly linear in the case of L_{K} and L_{FIR} and nonlinear for L_{B} and D_{25}^2 . The tightest correlations are with L_{FIR} and, for spiral galaxies with $T = 3-5$, with L_{K} , whereas the correlation with D_{25}^2 is the poorest. Due to the nonlinearity of the correlation, the ratio $M_{\text{H}_2}/L_{\text{B}}$ changes with L_{B} which has to be taken into account when comparing it to other samples. We describe a deficiency parameter, defined in analogy to the deficiency parameter for the atomic gas as the difference between the logarithm of the expected molecular gas mass and the logarithm of the observed molecular gas mass. The expected molecular gas mass can be calculated from any of the parameters studied by us (L_{B} , D_{25}^2 , L_{K} , L_{FIR}) using the correlation coefficients listed in Table 7.
3. We applied these relations and the resulting expressions to three samples from the literature (Perea et al. 1997; Casasola et al. 2004). For the sample of Casasola et al. and the sample of strongly interacting galaxies of Perea et al., we found clear evidence for an enhancement of M_{H_2} in comparison to L_{B} and L_{K} , while for a sample of weakly interacting galaxies from Perea et al. no difference with respect to the AMIGA sample was found. A possible reason for this difference could be a higher degree of interaction in the first two samples.
4. We derived a mean molecular gas depletion time, τ_{dep} (defined as $M_{\text{H}_2}/\text{SFR}$), of $\log(\tau_{\text{dep}}) = 9.0$ yr for spiral galaxies ($T = 3-5$) and a slightly lower value of $\log(\tau_{\text{dep}}) = 8.9$ yr for all morphological types (both values for a Kroupa IMF), in reasonable agreement with other studies of nearby galaxies (Bigiel et al. 2011; Saintonge et al. 2011).
5. No good correlation was found between M_{H_2} and M_{HI} . The ratio between the molecular and the atomic gas mass decreases significantly from early to late-type galaxies, with a difference of up to a factor of 10. The ratio $M_{\text{H}_2}/M_{\text{HI}}$ of the AMIGA galaxies is well below 1 for all morphological types, with a mean value of $\log(M_{\text{H}_2}/M_{\text{HI}}) = -0.72$ for galaxies of type $T = 3-5$. We compared our values to those of other noninteracting samples and found that the AMIGA galaxies had the lowest values for all spiral galaxies.
6. We used our data to compare the disk averaged surface densities of the molecular, Σ_{H_2} , and molecular+atomic gas, $\Sigma_{\text{H}_2+\text{HI}}$, to those of the SFR , Σ_{SFR} . We found a good correlation between the logarithms of Σ_{H_2} and Σ_{SFR} , with a slope close to 1. No correlation with of Σ_{SFR} with $\Sigma_{\text{H}_2+\text{HI}}$ was found.

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Appendix A: CO Spectra

Figure [A.1](#) shows the CO(1–0) profiles of the detections and tentative detections observed by us at the IRAM 30 m telescope and Fig. [A.2](#) those observed at the FCRAO 14 m telescope.

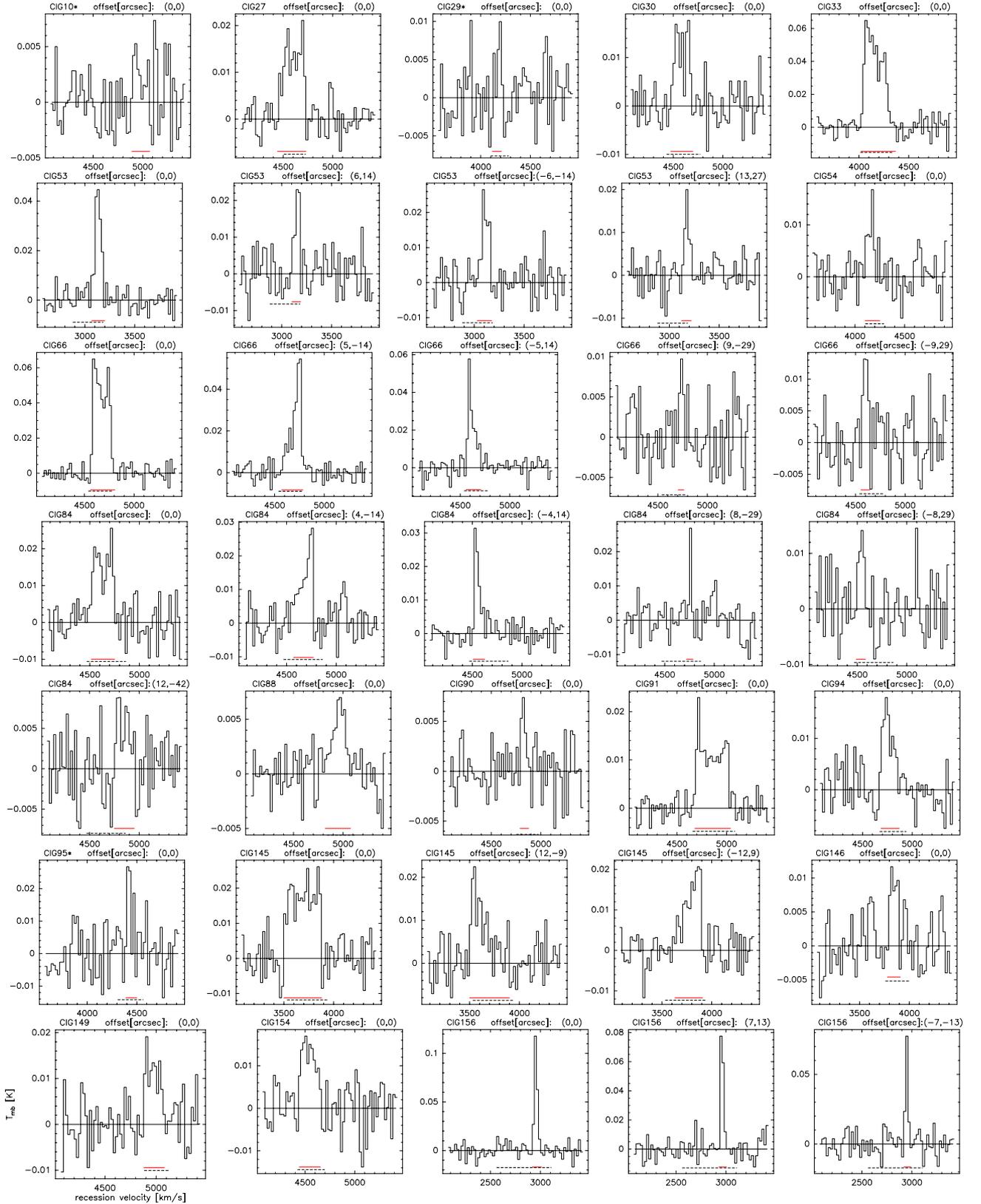


Fig. A.1. CO(1–0) spectra for the galaxies detected with the IRAM 30 m telescope. The x -axis represents the recession velocity in km s^{-1} and the y -axis the main beam brightness temperature T_{mb} in K. The spectral resolution is 20.8 km s^{-1} in most cases except for some individual galaxies for which a higher or lower resolution was required to clearly show the line. The full (red) line segment shows the line width of the CO line adopted for the determination of the velocity integrated intensity. The dashed (black) line segment is the HI line width at 20% peak level, W_{20} . An asterisk next to the name indicates a marginal detection.

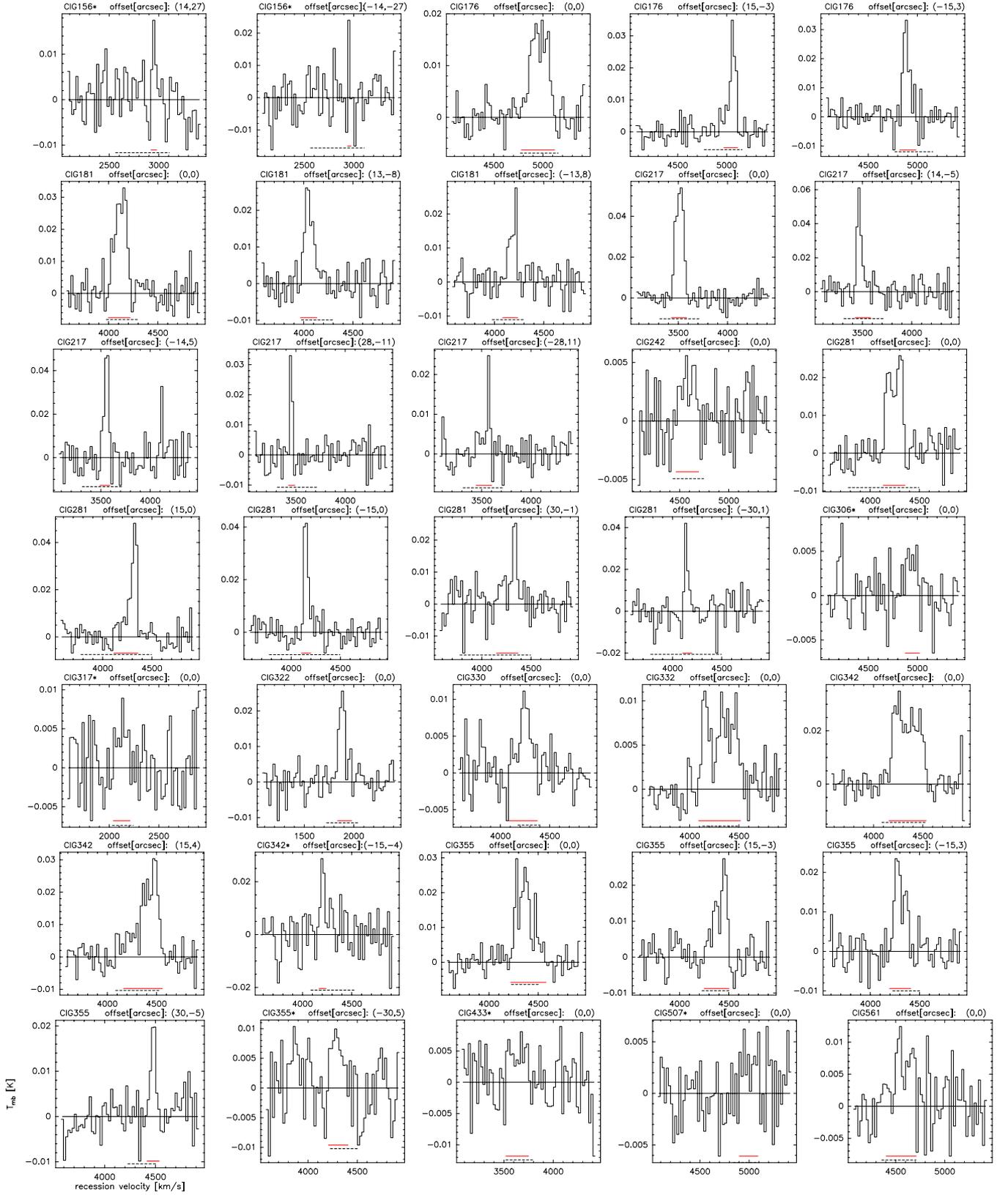


Fig. A.1. continued.

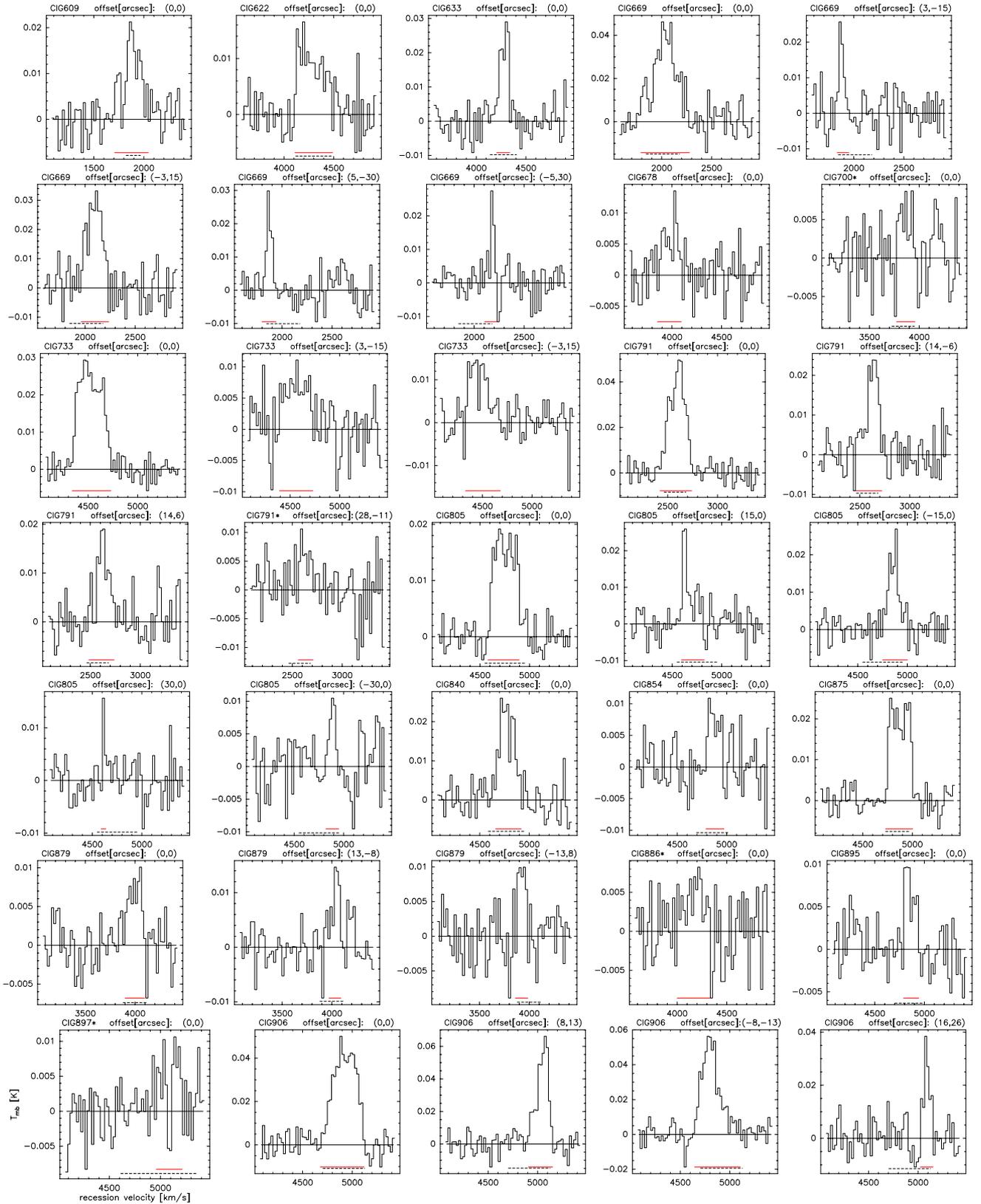


Fig. A.1. continued.

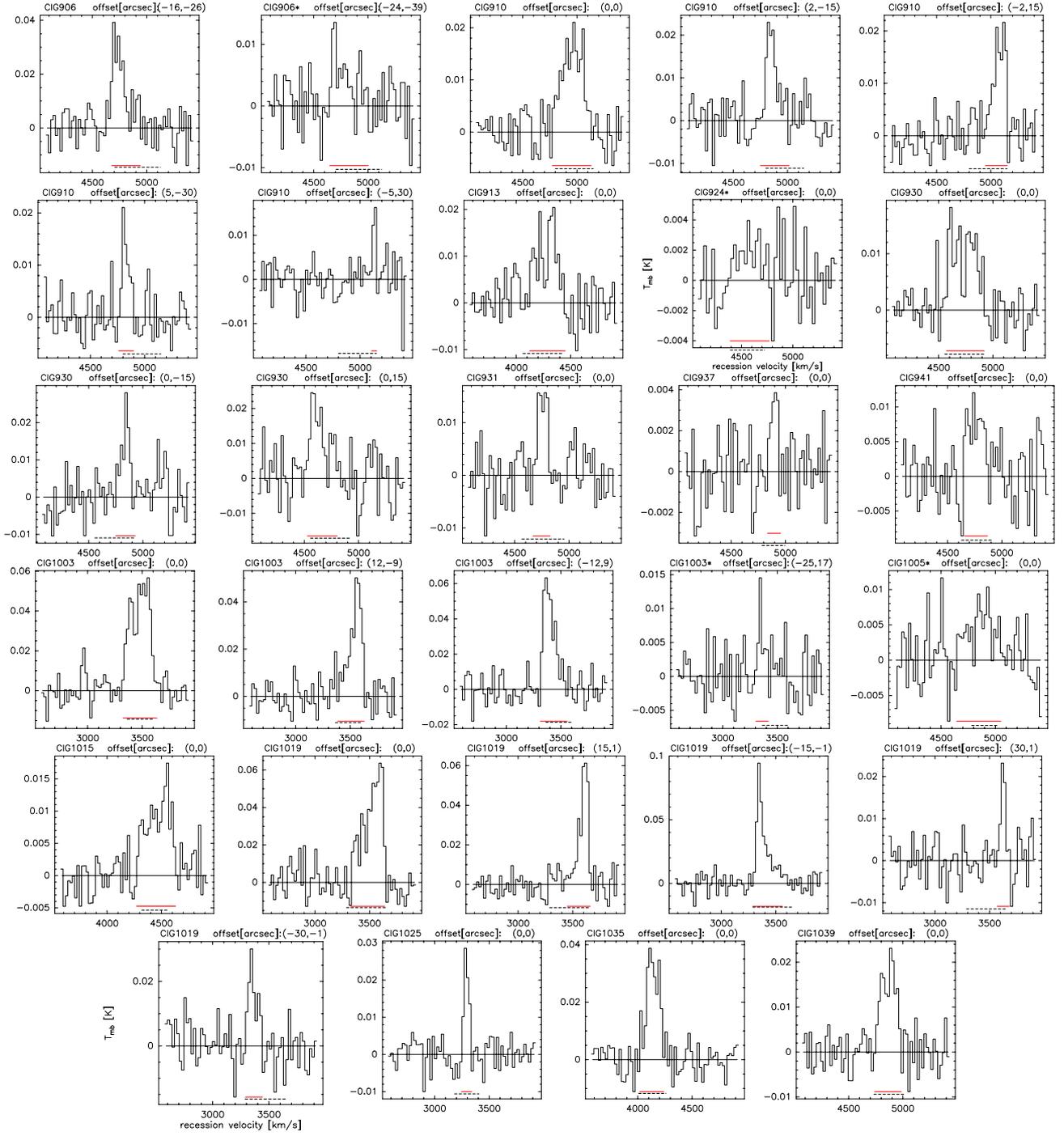


Fig. A.1. continued.

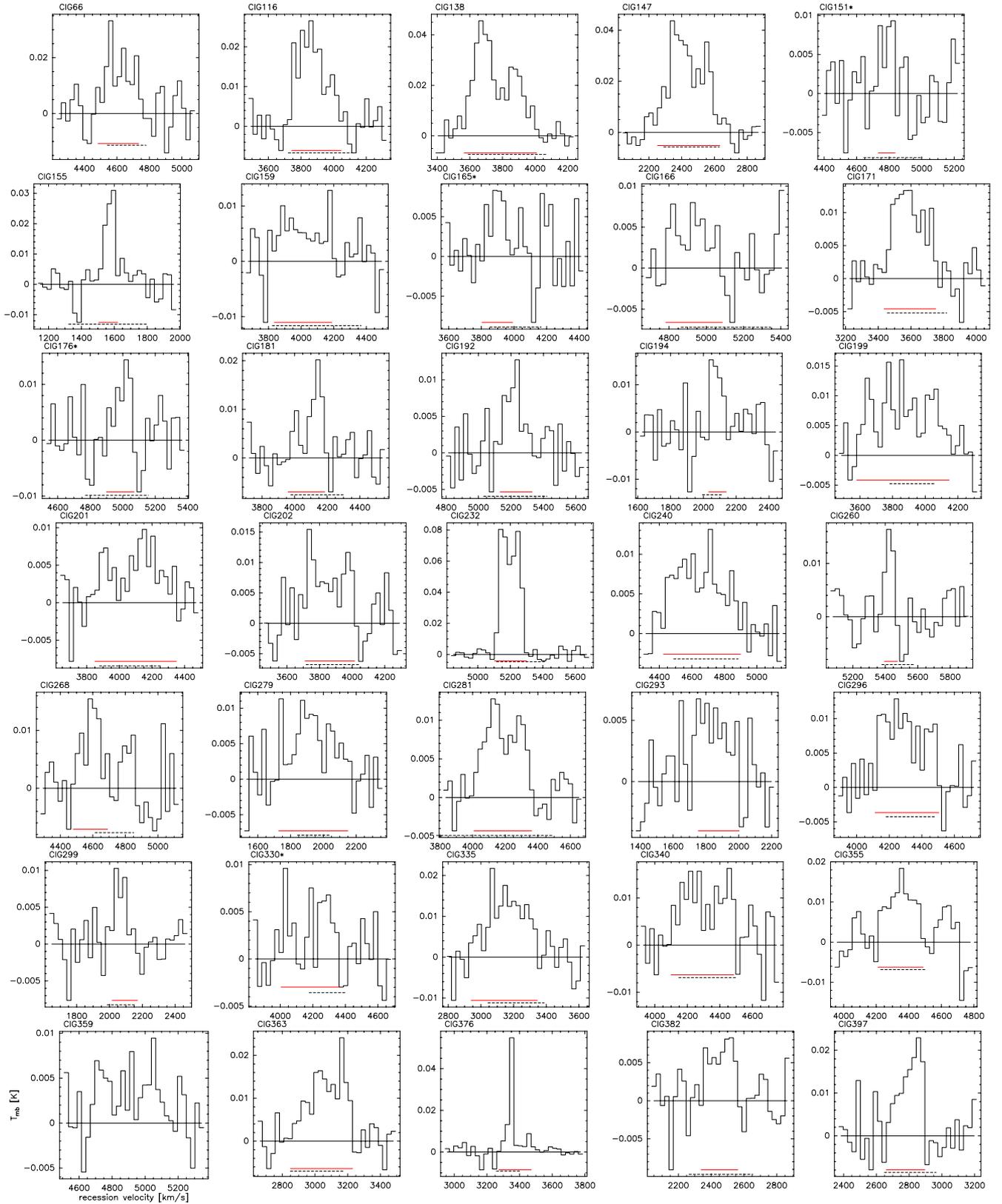


Fig. A.2. CO(1–0) spectra of the galaxies detected with the FCRAO telescope. The spectral resolution is 13.1 or 26 km s^{-1} , depending on the spectral shape and rms noise. The x -axis represents the recession velocity in km s^{-1} and the y -axis the intensity in K in the T_{mb} scale. The full (red) line segment shows the line width of the CO line adopted for the determination of the velocity integrated intensity. The dashed (black) line segment is the HI line width at 20% peak level, W_{20} . An asterisk next to the name indicates a marginal detection.

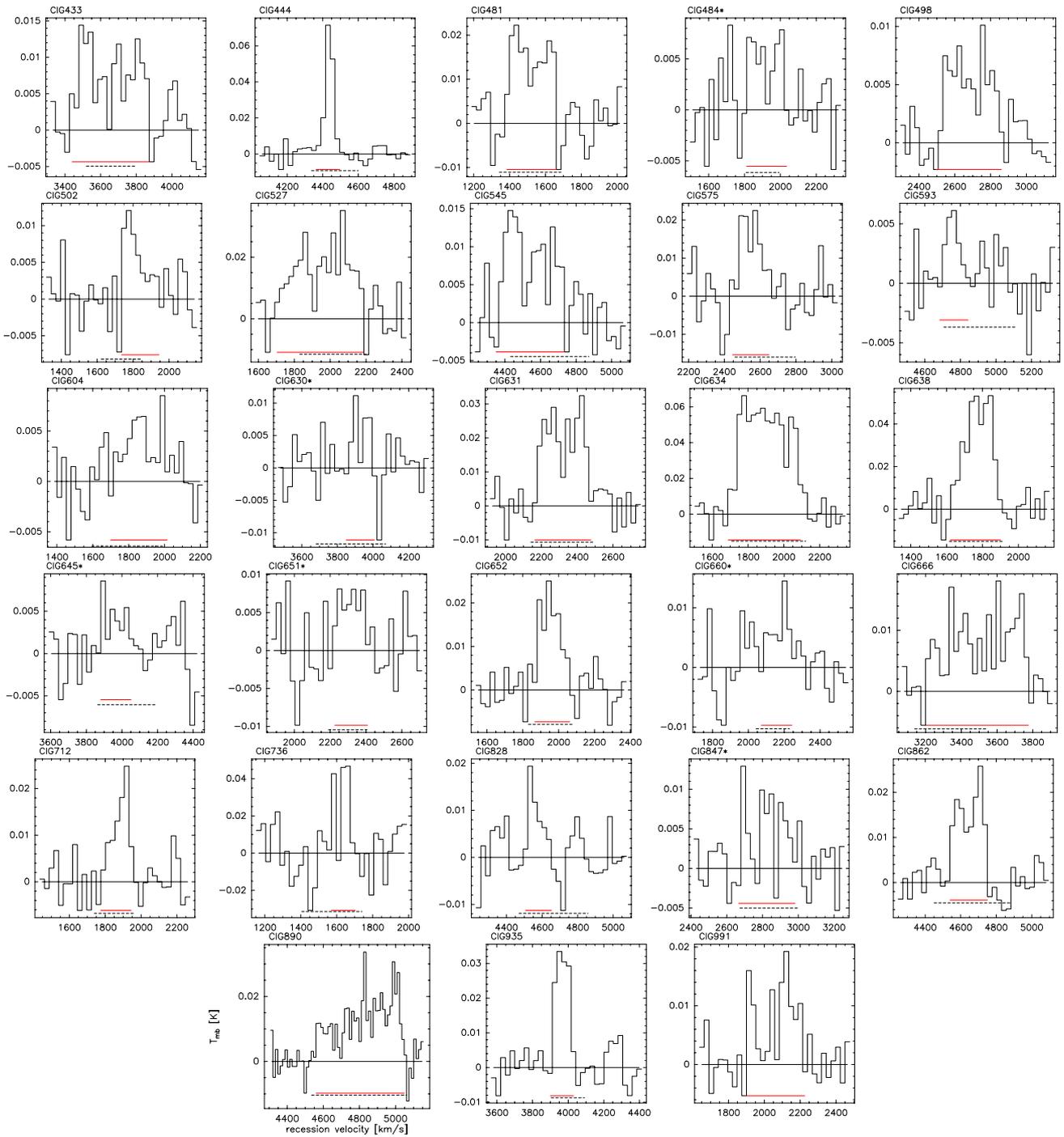


Fig. A.2. continued.