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CO(1 – 0) emission from luminous infrared galaxies in the southern hemisphere

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Abstract. CO (1 – 0) emission was detected from 28 high luminosity IRAS galaxies in the southern sky, selected from a sample of galaxies with 60 μm IRAS fluxes > 4.5 Jy and IR luminosities $> 10^{11}\,L_\odot$. These galaxies have total masses of H_2 in the range of 0.6–6 $10^{10}\,M_\odot$, namely 2–20 times the mass of molecular gas in the Milky Way. The IR luminosities per nucleon of molecular gas, $L_{IR}/M(H_2)$, are in the range of 10–80 $L_\odot/M_\odot$. This is 5–40 times the global value of this ratio in the Galaxy averaged over the whole disk. The optical morphology and the large masses of molecular gas found among the 12 galaxies of this sample with $L_{IR} > 10^{12}\,L_\odot$ suggest that ultraluminous IR galaxies are mergers of giant spiral galaxies.

Key words: Galaxies: active – infrared: kinematics and dynamics of – interstellar medium: clouds

1. Introduction

The Infrared Astronomical Satellite Survey (IRAS) revealed that a considerable fraction of extragalactic objects have total luminosities dominated by far-infrared (FIR) emission (Soifer et al., 1984). In most of these galaxies the FIR flux appears to come from dust heated as a consequence of intense star formation. However, as the FIR emission rises above $L_{IR} > 10^{11}\,L_\odot$, in addition to starbursts, these objects seem to be increasingly powered by an active nucleus. Sanders et al. (1988) have proposed that galaxies that radiate in the IR as much energy as quasars, namely, $> 10^{12}\,L_\odot$ in the 8 μm–1000 μm wavelength band, are dust enshrouded quasars. Although these ultraluminous IR galaxies are more numerous than optically selected quasars, our examination of the IRAS archival data shows that there are only a few tens of this type of galaxies in the Local Universe ($z < 0.1$).

Since interstellar cold gas is the fuel for intense star formation, studies of the molecular gas content in IR luminous galaxies are of importance for our understanding of the ultimate source of the energy radiated by these systems. The detection of CO (1 – 0) line emission at 2.6 mm from luminous IR galaxies (Young et al., 1984; Sanders and Mirabel, 1985; Sanders et al., 1987; Mirabel et al., 1988) has demonstrated that a common property of luminous IR galaxies is an abundant supply of molecular gas. Furthermore, most galaxies with IR luminosities above $10^{12}\,L_\odot$ exhibit OH megamaser emission, which in addition to large contents of molecular gas and warm IR photons, seem to require an active nucleus (Martin et al., 1989; Henkel and Wilson, 1989).

In this paper we present the data from a CO (1 – 0) survey of a sample of galaxies in the southern hemisphere limited in IR flux and IR luminosity. This survey is complementary of the survey conducted by Sanders et al. (1990) from the northern hemisphere, and provides the molecular gas content in southern objects that have $L_{IR} > 10^{11}\,L_\odot$. The analysis of the relations between the CO (1 – 0) emission with the optical, IR, and radio properties for this sample of galaxies will be deferred to a following paper.

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2. Galaxy sample and observations

We have observed 33 southern galaxies ($\delta < 0°$) with 60 μm IRAS fluxes > 4.5 Jy and intrinsic IR luminosities $> 10^{11}\,L_\odot$. Among these galaxies there are 12 ultraluminous systems with IR luminosities $> 10^{12}\,L_\odot$. Using the 15-m Swedish-European Submillimeter Telescope (SEST) at La Silla, Chile, during 24–26 June, 1988 (Mirabel et al., 1988), and 1–8 June 1989, we detected CO (1 – 0) emission from 28 objects up to redshifts of 38000 km s^{-1}.

A detailed account of the SEST and its performance was given by Booth et al. (1989). The telescope beamsize at 115 GHz is 44″ (FWHP), and the main beam efficiency is 0.71 with a spillover and scattering efficiency $\eta_{fss} = 0.92$. Pointing errors were of the order of 5″. For the SEST observations we used a single-polarization Schottky receiver with a 728 channel acousto-optical spectrometer covering 500 MHz (1300 km s^{-1}), which provided a velocity resolution of ~1.8 km s^{-1}.

The SEST data were taken in a dual beam switch mode placing the source alternatively in two beams to eliminate asymmetries between the source signal path and the reference signal path. The observations at SEST were taken over a total of 145 h of good weather conditions, with system temperatures that were in the range of 360–390 K. To obtain adequate signal-to-noise ratios we spent between 1 and 8 h of integration on each source, depending on the intensity of the signal.

Table 1. CO (1 − 0) properties of luminous infrared galaxies ($L_{IR} > 10^{11}\ L_\odot$) in the southern hemisphere [a]

(1) IRAS Other	(2) RA (1950)	(3) Dec (1950)	(4) V_{opt} ($km\ s^{-1}$)	(5) V_{CO} ($km\ s^{-1}$)	(6) I_{CO} ($K\ km\ s^{-1}$)	(7) $M(H_2)$ ($10^{10}\ M_\odot$)	(8) L_{IR} $10^{11}\ L_\odot$	(9) $L_{IR}/M(H_2)$ ($L_\odot/M_\odot$)
00402-2350	00^{h}40^{m}17.^{s}5	−23°50′02″	6647	6786	8.9	1.5	2.5	17
NGC 232								
01077-1707	01 07 42.1	−17 07 01	10040	10514	4.9	2.0	3.9	20
MCG-03-04-014								
01159-4443	01 15 56.9	−44 43 26	6855	6750	4.4	0.7	2.2	31
E 244-G 12								
01364-1042	01 36 24.1	−10 42 25	14250	14527	1.9	1.5	5.9	39
04454-4838	04 45 27.9	−48 38 45	15948	15912	1.2	1.1	6.3	57
05189-2524 [b]	05 18 58.6	−25 24 40	12706	12816	2.6	2.3	12.3	54
06035-7102	06 03 34.6	−71 02 58	23684	23888	1.3	2.7	13.0	48
06206-6315	06 20 40.3	−63 15 51	27500	27512	2.1	5.9	13.0	22
06219-4330	06 21 54.0	−43 30 06	19103	–	–	–	7.8	–
06259-4708	06 25 59.6	−47 08 41	11630	11802	3.3	1.7	6.6	39
06592-6313	06 59 15.1	−63 13 37	6882	6897	3.4	0.6	1.4	23
07160-6215	07 16 03.9	−62 15 07	3237	3272	23.7	> 0.9	1.2	< 13
08520-6850	08 52 04.9	−68 50 29	13660	13540	1.1	0.9	5.2	55
09111-1007	09 11 11.1	−10 07 01	16438	16273	2.3	2.3	8.9	39
10039-3338	10 03 54.8	−33 38 43	10223	–	–	–	4.4	–
IC 2545								
10257-4338	10 25 42.9	−43 38 56	2697	2818	50.2	1.5	3.9	26
NGC 3256								
11506-3851	11 50 40.2	−38 51 10	3076	3085	9.2	> 0.3	1.4	< 43
E 320-G 30								
13001-2339	13 00 11.1	−23 39 14	6446	6360	5.8	0.9	2.5	28
M-04-31-023								
14348-1447 [b]	14 34 52.3	−14 47 24	24677	24732	1.7	6.0	18.4	31
14378-3651	14 37 53.4	−36 51 44	20277	20444	1.0	1.5	12.1	82
16330-6820	16 33 00.2	−68 20 06	14082	13924	7.3	4.8	7.3	15
E 69-IG 6								
17208-0014	17 20 48.2	−00 14 17	12836	12852	7.0	4.3	22.0	51
18093-5744	18 09 20.2	−57 44 28	5200	5169	6.0	0.7	2.3	31
IC 4687								
18293-3413	18 29 22.4	−34 13 43	5449	5480	32.6	3.6	5.4	15
18341-5732	18 34 08.4	−57 32 05	4601	4648	11.6	0.9	1.6	17
IC 4734								
19115-2124	19 11 32.3	−21 24 22	14608	14680	3.9	3.1	6.9	22
E 593-IG 8								
19254-7245	19 25 27.8	−72 45 39	18500	18479	2.4	3.0	10.7	36
20087-0308	20 08 46.4	−03 08 53	31600	–	–	–	22.6	–
20100-4156	20 10 05.8	−41 56 40	37800	–	–	–	36.4	–
20414-1651	20 41 28.3	−16 51 13	26107	–	–	–	13.5	–
20551-4250	20 55 09.3	−42 50 38	12767	12940	3.1	1.9	10.0	53
E 286-IG 19								
22132-3705	22 13 12.9	−37 05 39	3447	3469	14.0	> 0.6	1.4	< 22
IC 5179								
22467-4906	22 46 42.7	−49 06 53	12450	12921	2.2	1.4	5.6	41
E 239-IG 2								
22491-1808 [b]	22 49 09.6	−18 08 21	23312	23170	0.9	2.8	12.9	46
23128-5919	23 12 50.6	−59 19 38	13267	13403	1.9	1.3	9.0	69
E 148-IG 2								
23179-6929	23 17 59.7	−69 29 20	12460	12438	3.3	1.9	4.8	25

[a] $H_0 = 75\ km\ s^{-1}\ Mpc^{-1}$.
[b] CO data from Sanders et al. (1990).

3. Results

In Table 1 are given the properties and CO $(1-0)$ parameters of the complete sample of 36 southern galaxies with 60 µm fluxes >4.5 Jy and $L_{IR} > 10^{11}\, L_{\odot}$. The CO $(1-0)$ data for 33 objects of this sample are from the SEST survey reported in this paper. Data for the remaining 3 galaxies of this sample come from the survey conducted from the north by Sanders et al. (1990). In column (1) are given the IRAS and alternative names. In columns (2) and (3) the positions observed, which were taken from the IRAS Point Source Catalogue. The CO (1–0) transition was observed at a sky frequency that placed the optical heliocentric velocity listed in column (4) at the center of the spectrometer. Column (5) gives the centroid heliocentric velocities of the CO $(1-0)$ profiles. Column (6) gives the total integrated CO $(1-0)$ line intensity $I_{CO} = \int T_R^*\, dV$ (K km s^{-1}), where $T_R^* = T_A/\eta_{fss}$, is the antenna temperature corrected for the forward spillover and scattering efficiency of the telescope, η_{fss}. The uncertainty in I_{CO} is typically 20%. The total masses of molecular hydrogen $M(H_2)$ given in column (7) were estimated using the empirical relation $M(H_2) = 5.8\, [(\pi/4)\, d_b^2\, I_{CO}]$, where d_b (pc) is the half-power diameter of the telescope beam at the distance of the source. For galaxies at distances where $d_b < 10$ Kpc, we consider the $M(H_2)$ listed in Table 1 as a lower limit. The constant 5.8 was taken from Sanders et al. (1984). Distances to each of the objects have been calculated assuming $H_0 = 75$ km s^{-1} Mpc^{-1}. L_{IR} in column (8) represents the total IR luminosity between 8 µm and 1000 µm, which was computed using the fluxes in the four IRAS bands, following the prescription outlined by Pérault et al. (1990). Column (9) gives the $L_{IR}/M(H_2)$ ratio in solar units.

Figure 1 shows the CO (1–0) profiles of all 28 galaxies detected with SEST. Instrumental baselines were substracted by fitting straight lines to the data. The spectra have been smoothed to a resolution of 20 km s^{-1}. During the June 1989 run, narrow interference spikes that appeared at some tuning frequencies affected few channels at the high velocity end of the spectra, and the profiles in Fig. 1 have been corrected by interpolation using unaffected adjacent channels.

For comparison of the performances of the telescopes used in the surveys of luminous IR galaxies conducted from the north (Sanders et al., 1990), and from the south (this paper), we observed the galaxies IRAS 09111-1007 and IRAS 17028-0014 with the 12-m NRAO telescope and the SEST. The spectra of these two galaxies obtained with the 12-m NRAO telescope are superimposed by means of small dots on the SEST profiles in Fig. 1. The NRAO data on these two galaxies have about 3 times the observing time used at SEST. The SEST and NRAO data show excellent agreement with I_{CO} values having discrepancies <10%.

The non-detections of CO in 5 of the sample galaxies should not be used to set upper limits on I_{CO}. The optical velocities we have used to tune the receiver may have errors of up to several hundred km s^{-1}, and the detection of velocity-broad weak signals with a 1300 km s^{-1} width spectrometer may be difficult in some instances. In fact, soon after the SEST observations reported here, one of us obtained high dispersion spectra of several of the sample galaxies with the 4-m Cerro Tololo telescope. It was found that the redshift of IRAS 20087-0308 differs by 500 km s^{-1} with respect to that listed in Table 1. Furthermore, optical imaging showed that the brighter galaxy of the pair IRAS 10039-3338 has a discrepancy of 35″ with the position observed (listed in Table 1 and taken from the IRAS Point Source Catalogue). Therefore, for 2 of the 5 galaxies not detected we have already found errors in the original data base of our program of CO $(1-0)$ observations. We believe that all galaxies of this sample can be detected with the present millimeter receiver system at SEST, and the galaxies not detected will be reobserved in a future session of observations.

4. Discussion

The primary result of this survey is that the IR luminous galaxies of this southern sample are extremely rich in molecular gas with masses in the range of 0.6–6.0 $10^{10}\, M_{\odot}$. These masses are 2–20 times the mass of molecular gas in the Milky Way, and on the average substantially larger than the total H_2 masses in nearby luminous spiral galaxies such as M 101. The high abundance of molecular gas in these systems may be due to the contribution of molecular gas from more than one galaxy within the telescope beam, combined with an enhancement of conversion of H I into H_2 (Mirabel and Sanders, 1989).

The mass of interstellar molecular gas was computed from the CO luminosity using a "standard" CO-H_2 conversion factor obtained by Sanders, Solomon and Scoville (1984). From galactic GMC's (Scoville et al., 1987), and from galactic γ-ray measurements (Bloemen et al., 1986), values that are within 30% the one we use here are derived.

Despite the controversy about the CO-H_2 conversion factor, CO $(2-1)$/CO $(1-0)$ measurements in extremely luminous IR galaxies by Casoli et al. (1988), seem to indicate that the bulk of CO emission from this type of galaxies is optically thick and come from cold gas as in the galactic GMC's.

Figure 2a shows that as previously found for samples of IR luminous galaxies in the northern hemisphere (Sanders and Mirabel, 1985; Sanders et al., 1986), this sample of southern galaxies also shows a general trend of increasing $M(H_2)$ with L_{IR}. Although the correlation in Fig. 2a has a significant dispersion, for a given L_{IR}, one can anticipate the mass of molecular gas $M(H_2)$ within factors of 2–3.

Figure 2b shows that the energetics of the molecular clouds, given by the IR luminosity per nucleon of interstellar gas, L_{IR}/M(H_2), has values in the range of 10–80 $L_{\odot}/M_{\odot}$. This is larger than the average ratios found in insolated spirals and classical starbursts such as M 82. The IR flux per nucleon of interstellar gas in luminous IR galaxies is comparable to that found in the most active galactic molecular clouds with H II regions (Mooney and Solomon, 1988). If the IR luminosity is considered a measure of the massive star formation rate, we must conclude that in the galaxies of this sample a large fraction of the molecular gas will be depleted in time scales of 1–5 10^8 yr.

Melnick and Mirabel (1990) recently obtained New Technology Telescope optical images of the ultraluminous objects ($L_{IR} > 10^{12}\, L_{\odot}$) of this sample of galaxies. In all cases the high resolution optical images reveal either double nuclei, wisps, or long slender tails indicative of a characteristic distance between colliding galaxies of <10 kpc. This morphology, together with the extreme large abundances of molecular gas, suggest that luminous IR galaxies represent colliding, and in the most extreme cases, mergers of giant spiral galaxies. The high resolution images of these galaxies also reaffirm the idea that the high luminosity-to-mass ratios are related to the strenght of galaxy-galaxy interactions (Solomon and Sage, 1988; Mirabel and Sanders, 1989), namely with the galactic environment, rather than only with the intrinsic cloud properties.

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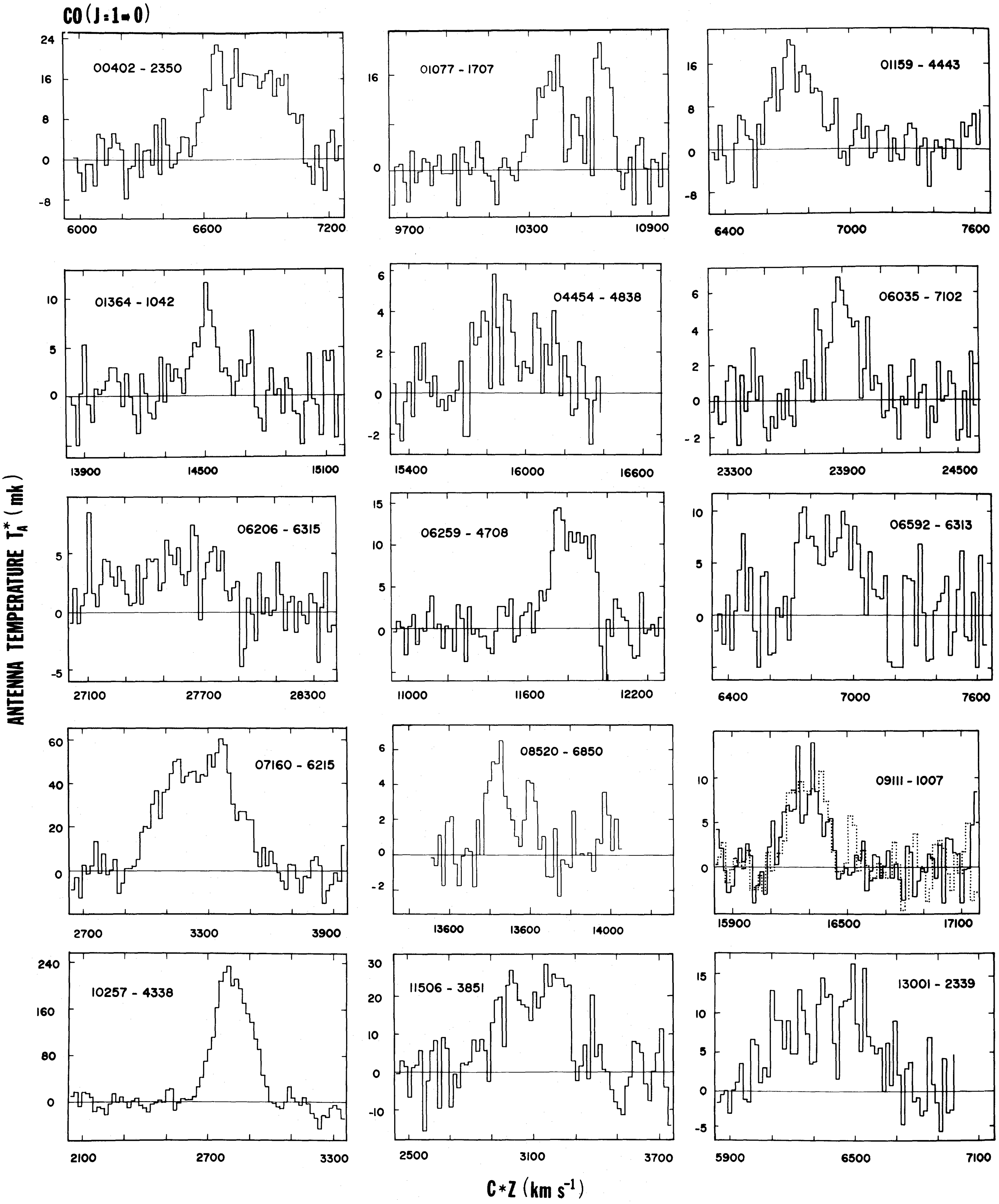

Fig. 1. CO($J=1-0$) emission profiles for 28 high luminosity galaxies detected with SEST. For comparison also are shown by dots the profiles for IRAS 09 111-1007 and IRAS 17 208-0014 obtained with the NRAO 12-m telescope. The spectra have been smoothed to a resolution of 20 km s^{-1}

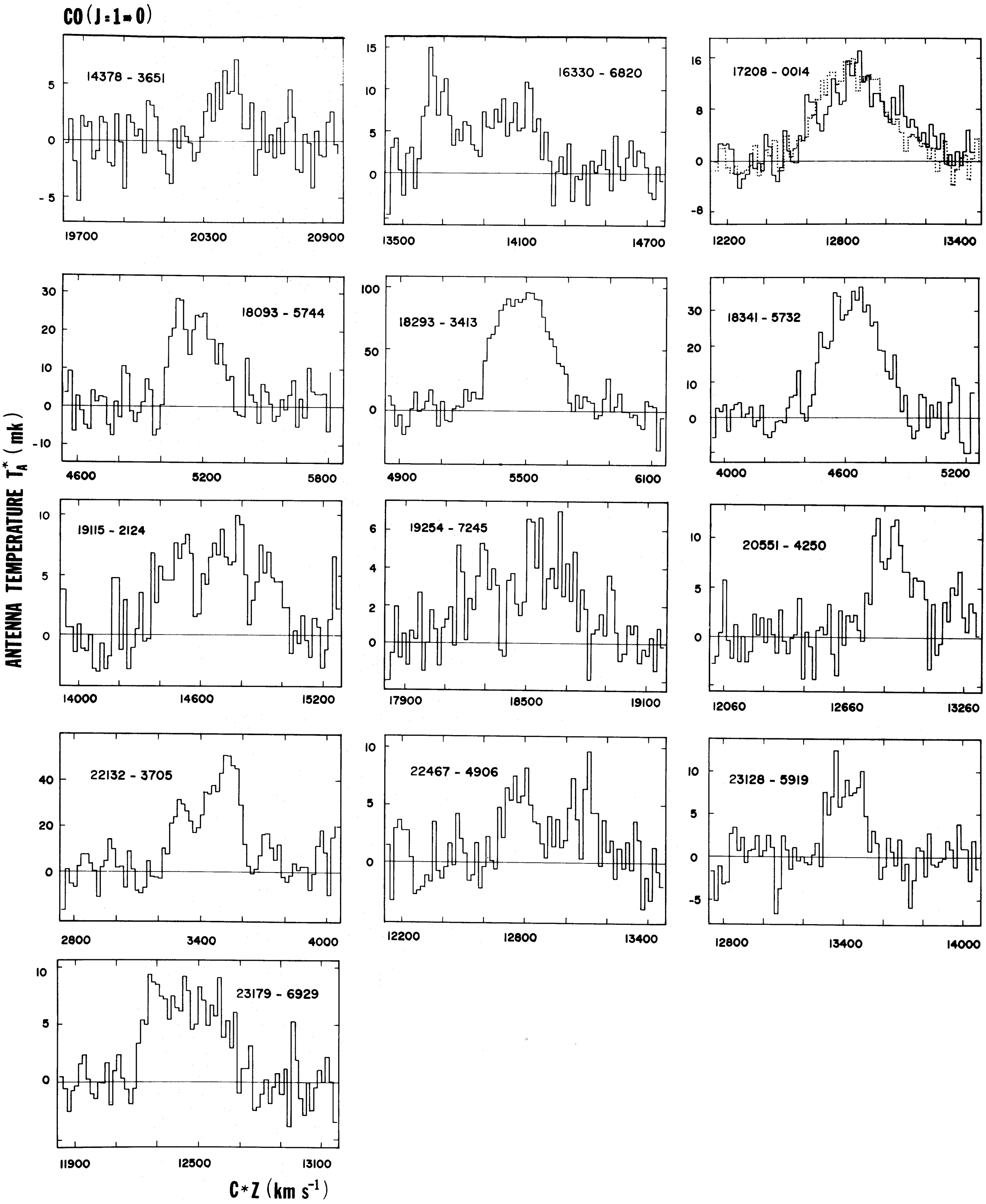

Fig. 1 (continued)

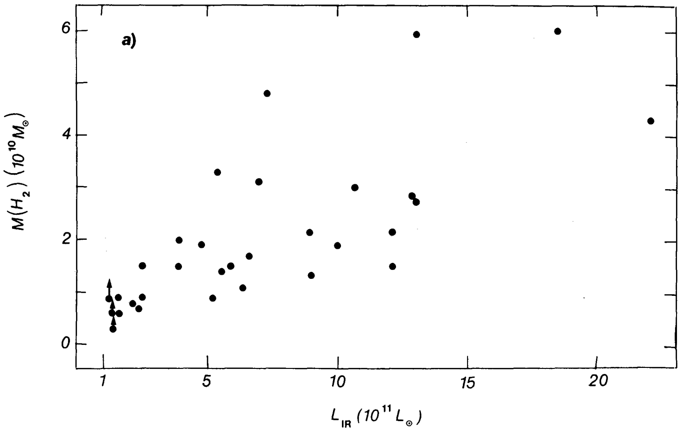

Fig. 2a. Total molecular mass of H_2 determined from the CO (1 − 0) observations vs. the total IR luminosity in the 8 μm–1000 μm band for the 28 IR luminous galaxies detected in the southern survey with SEST

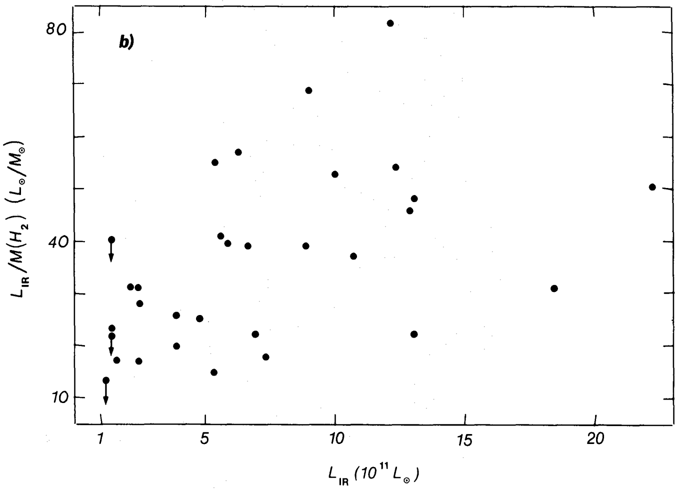

Fig. 2b. The ratio of total IR luminosity to total H_2 mass in molecular clouds vs. the total IR luminosity for the same sample of galaxies

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