Dust and molecular gas in magellanic type galaxies

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Abstract

We have observed the CO line and thermal dust continuum emission at 1.3 mm in a FIR flux limited sample of magellanic type galaxies using the SEST and the MRT. The data allow to put constraints on the spatial distribution of both types of emission in comparison with earlier type galaxies. A direct comparison of CO and dust luminosity allows to study the conversion factor of CO luminosity to the mass of molecular hydrogen and the molecular gas-to-dust ratio.

1 Introduction

The amount of molecular gas is a decisive quantity for the understanding of galaxies. As H_2 lacks a permanent dipole moment it cannot easily be observed directly in emission or absorption. Therefore indirect methods are used. The most commonly applied method considers the line emission of CO as a tracer for the total amount of molecular gas. Though the line emission of the most abundant CO isotope is optically thick and therefore provides no direct information on column densities, an empirical relation between CO luminosity $L_{\rm CO}$ and H_2 mass $M(\rm H_2)$ has been established for molecular clouds in the Milky Way and nearby galaxies: $M(\rm H_2) = \beta\ L_{\rm CO}$. Many attempts have been made to gauge the corresponding conversion factor β in extragalactic systems. Especially in low-metallicity dwarf galaxies the use of a standard conversion factor derived for galactic clouds would result in negligible amounts of molecular gas. Most attempts to derive β in low-metallicity environments focus on nearby dwarfs where the emission at mm wavelengths can be resolved and compared to different mass tracers of the molecular clouds like virial mass, gamma ray emissivity, optically thin molecular lines and others. Israel (1997) uses IRAS FIR surface brightness data and HI column densities to derive the H_2 content towards CO clouds in the LMC, SMC and a few other magellanic type galaxies. As a result the conversion factor shows a dependency on the metallicity and the ambient radiation field per nucleon. Still it remains to be shown that the same values for β gauged from a few neighbouring systems can be applied to the bulk of apparently small dwarfs where only long-term ON-OFF observations lead to a detection at mm wavelengths. We have compared the CO luminosity with the dust mass as a second tracer for the amount of interstellar gas derived from our observations at 1.3 mm and IRAS data. Given a molecular gas-to-dust ratio R the mass of H_2 can be derived using $M(\rm H_2) = R\ M(\rm dust)$. Our observations do not allow to determine the fundamental parameters β and R independently but at least make their ratio R/β an observational quantity.

2 The Sample

The dwarf galaxy sample contains 70 sources of morphological type I(B)m and S(B)m extracted from a compilation of Melisse & Israel (1993a, 1993b) who have determined the FIR fluxes (or upper limits) in the four IRAS bands for 278 magellanic type galaxies. To ensure a considerable

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coverage of the sources with a single beam and concerning technical limitations for the ON–OFF separation only galaxies with a major optical axis at the $25^{\rm th}$ mag arcsec^{-2} isophote $D_{25} \leq 180''$ were taken into account. As a second selection criterion only galaxies with IRAS fluxes at 100 μm $S_{100\mu\rm m} \geq 1000$ mJy were extracted leading to a presumably sufficient detection probability needed for a survey. This selection of IRAS bright dwarf galaxies most probably introduces a bias towards an enhanced star formation activity in the observed systems which has to be kept in mind. Nevertheless, this study has to be considered as a first attempt to observe both CO **and** thermal dust emission in a complete sample of FIR selected dwarf galaxies at equal beamsizes. After characterizing the morphological types of the galaxies according to the RC3 the sample has been divided into two subsamples: (a) The **Im sample** contains magellanic irregulars and (b) the **Sm sample** contains magellanic type spirals. One aim of this project is to study the relationship between dwarf galaxies and 'normal' galaxies concerning their physical properties as derived from dust and CO observations, where 'normal' in this context refers to galaxies of morphological type S0 to Sd and not classified as dwarfs. For the purpose of comparison a sample of 181 spirals is used which has been compiled and observed by R. Chini and E. Krügel (Chini et al. 1992, 1996, 2001; Krügel et al. 1988a, 1988b, 1990). The selection again is based on FIR flux at 100 μm and angular size. Only sources with $S_{100\mu\rm m} \geq 9$ Jy are taken into account. A thorough review of the available optical spectroscopy data and using FIR colours as a secondary calibrator has led the authors to introduce a classification into three subsamples with respect to the star formation activity: *normal* (71), *starburst* (80) and *Seyfert* (AGN) galaxies (30).

3 Observations

3.1 CO observations

The CO(1–0) and CO(2–1) line transitions were observed using the 15m *Swedish ESO Submillimetre Telescope* (SEST) and the *IRAM 30m Millimetre Radio Telescope* (MRT). The observations at the **SEST** were performed during November 1997, July and November 1999. To stabilize baselines a balanced ON–OFF dual beam switching mode was applied with a separation between the ON and OFF beams of $11'50''$ in azimuth at a frequency of 6 Hz. The dual channel 115/230 GHz SIS receiver was tuned to the central velocity of the HI distribution in each source. Spectra were obtained with two acousto–optical spectrometers providing a total bandwidth of 1 GHz and a resolution of 0.7 MHz per channel. The northern sources of the dwarf galaxy sample were observed with the **MRT** during October 1998, May 1999 and July 2000. A wobbler switching mode was performed at a frequency of 0.5 Hz with a beamthrow between $150''$ and $240''$ in azimuth depending on the size of the source. Two 3 mm SIS receivers and two 1.3 mm SIS receivers were used. The 3 mm SIS receivers were connected to a low resolution filterbank with a total bandwidth of 1 GHz and a resolution of 1 MHz. As backend for the 1.3 mm SIS receivers an autocorrelator was used providing a bandwidth of 512 MHz and a resolution of 1.25 MHz for each receiver.

CO observations were performed for 60 dwarf galaxies (29 Im, 31 Sm) of which 36 have been detected (13 Im, 23 Sm) leading to an overall detection rate of 60 % (Im: 45 %, Sm: 74 %).

3.2 Dust observations

The thermal dust continuum emission at 1300 μm has been observed at the SEST in July 1999. The continuum observations at the MRT took place in February, March and April 1998 and in April 1999. Observations at the MRT were carried out with the 37–channel bolometer array developed and built by the MPIfR, Bonn. Each channel of the array has a half power beamwidth of $11''$ (HPBW). The channels are arranged in a hexagonal structure with a pixel–to–pixel separation

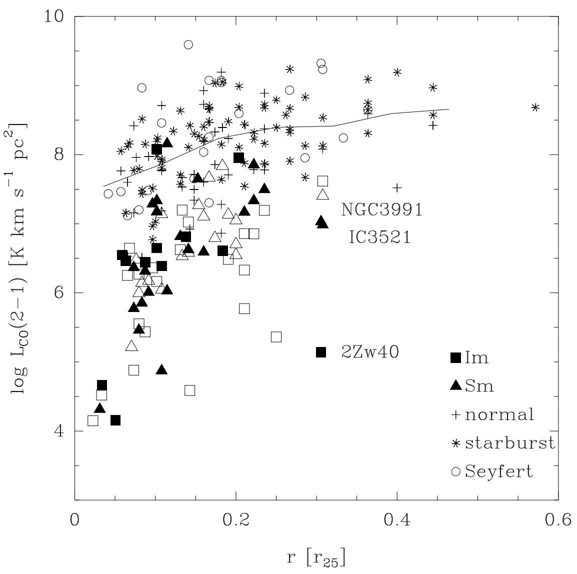

Figure 1: CO luminosity log $L_{\rm CO(2-1)}$ versus normalized radius r from MRT and SEST observations. Upper limits for Im and Sm galaxies are displayed as open squares and triangles respectively. The solid curve denotes the mean rise for all comparative galaxies. Fitting straight lines results in a gradient of 12.2±2.6 for the dwarf galaxies, where 2Zw40, IC 3521 and NGC 3991 are omitted. The comparative galaxies yield a mean slope of 2.9±0.5.

of 23″. All observations were made in a symmetrical ON–OFF mode with a beam separation between 70″ and 120″ in azimuth and a wobbling frequency of 0.51 Hz. To ensure that the channel positions with respect to the galaxy do not move, the integrations were carried out during those time intervals when the rotation of the array had its minimum. A more sophisticated reduction algorithm than the standard software was developed in the framework of NIC to reduce the high frequency skynoise. The new algorithms also allow the choice of arbitrary channels to derive the background emission. As a result an increased signal–to–noise ratio of about $10-15$ % is achieved for most observations. The details of the reduction algorithm are given in Albrecht (2001).

At the SEST the continuum observations were carried out using a single channel bolometer of the MPIfR. A dual beam switching mode (ON–OFF) with a separation of 120″ between the ON– and OFF–beam was applied for all observations.

The continuum observations have been carried out towards 52 dwarf galaxies (29 Im, 23 Sm) of which 28 have been detected (17 Im, 11 Sm) with a signal–to–noise ratio $S/N \geq 3$ leading to an overall detection rate of 54 % (Im: 59 %, Sm: 48 %).

4 Some Results

4.1 The spatial extent of CO emission

The measured CO emission originates from different observed fractions of the sources and cannot be compared directly for all galaxies. To put constraints on the spatial distribution of the line emission, the CO luminosities are plotted as a function of the normalized radius in Fig. 1. Both MRT and SEST data are included. The normalized radius is defined as the radius of the area of the source covered by the mm beam in units of the total optical radius (major axis) at the $25^{\rm th}$mag arcsec^{-2} isophote and reflects the observed fraction of the galaxies. As can be expected dwarf galaxies exhibit much lower values than the comparative sources at similar normalized radii. Moreover, dwarfs statistically show a steeper rise with increasing normalized radius in contrast to the comparative sources. In accordance with the low degree of central light concentration this reflects a rather flat spatial distribution of line emission in dwarfs, whereas in large spirals it is much more centrally concentrated.

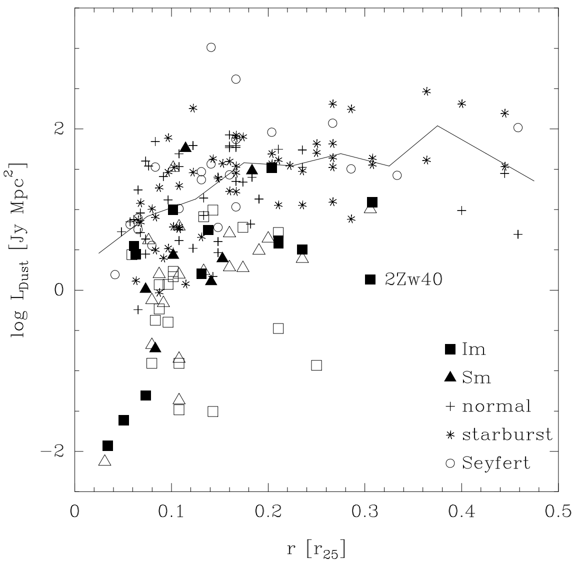

Figure 2: Dust luminosity log $L_{\rm dust}$ versus normalized radius r from MRT and SEST observations. The solid curve indicates the mean rise for all comparative galaxies. Open squares and triangles denote upper limits for Im and Sm galaxies respectively. Fitting straight lines to the data results in a gradient of 8.2±2.6 for the dwarf galaxies, where 2Zw40 is omitted. The comparative galaxies yield a mean slope of 2.7±0.5.

4.2 The spatial extent of dust emission

In Fig. 2 the central dust luminosity defined as $L_{\rm dust} = S_{\rm dust}\ D^2$ is plotted as a function of normalized radius. Both MRT and SEST data are included. Obviously, the dwarf galaxies exhibit a tendency towards lower dust luminosities as compared to earlier type galaxies at similar radii. Similar to the line radiation the dust emission appears to be much more concentrated towards the center in the comparative galaxies than in the dwarfs from a statistical point of view. In dwarfs the distribution of dust emission is flatter as the average gain in luminosity is more sensitive to the fraction of the source observed. This corroborates the classification scheme introduced by Rice et al. (1988) based on IRAS profiles of apparently large galaxies where Im and Sm sources typically show little or no enhanced emission from the nuclear region. In contrast, earlier type galaxies are more or less nucleus–concentrated.

4.3 Comparison of CO and dust

The simultaneous observation of CO line and dust continuum emission with equal beamsizes offers an unique opportunity to compare the two methods to derive the amount of molecular gas. The H_2 mass can be determined via the observed CO luminosity $M(H_2) = \beta\ L_{\rm CO}$ or the dust mass $M(H_2) = R\ M(\rm dust)$.

From the radiative transfer equation of the optically thin thermal emission of dust it follows that the net flux at 1.3 mm is a function of the macroscopic (mass and temperature) and microscopic properties (mass absorption coefficient κ) of the dust: $S_\nu = \kappa_\nu\ B_\nu(T_{\rm dust}) M_{\rm dust}\ D^{-2}$. To derive the dust mass we have determined the colour temperature using the IRAS flux at 100 μm and the observed flux at 1.3 mm by fitting a modified Planck function with an emissivity law $\kappa_\nu \propto \nu^2$. Under the assumption of equal microscopic dust properties in all galaxies we have fixed the mass absorption coefficient to κ =0.45 cm^2 per g of interstellar dust. The ratio of CO luminosity to dust mass then directly reflects the ratio of the fundamental unknowns: $L_{\rm CO}/M(\rm dust) = R/\beta$. In Fig. 3 this ratio is plotted as a function of normalized radius for MRT and SEST data. The starburst and Seyfert galaxies exhibit a slight decrease with increasing normalized radius while the ratio of the normal galaxies stays rather constant. On average Im and Sm galaxies attain the lowest values but with a large scatter. No distinctive gradient is apparent. Both the CO-H_2 conversion factor and the gas-to-dust ratio have been shown to be a function of metallicity. The differences of the ratio R/β between comparative and dwarf galaxies might thus result from different metallicities. Fig. 4

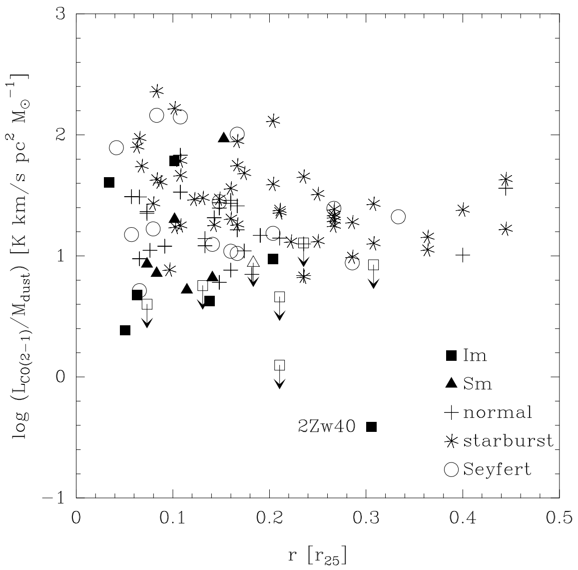

Figure 3: Ratio of CO(2–1) luminosity to dust mass as a function of normalized radius from MRT and SEST observations. Open squares and triangles denote upper/lower limits for Im and Sm galaxies respectively. The dwarf galaxies adopt a mean ratio of 23.6±29.5 [K km/s pc^2 M$_\odot^{-1}$] and the comparative galaxies yield 51.9±49.7 [K km/s pc^2 M$_\odot^{-1}$].

shows the dependence of $L_{\mathrm{CO}}/M(\mathrm{dust})$ as a function of absolute blue magnitude M_{B}. As most dwarfs in our sample lack relative oxygen abundance data, M_{B} has to serve as a rough indicator for metallicity in the systems. The MRT data exhibit a rough increase of R/β with increasing absolute blue magnitude. Still the difference in R/β for individual dwarfs with comparable values of M_{B} is large leading to the conclusion that the ratio cannot be dominated by the metallicity alone.

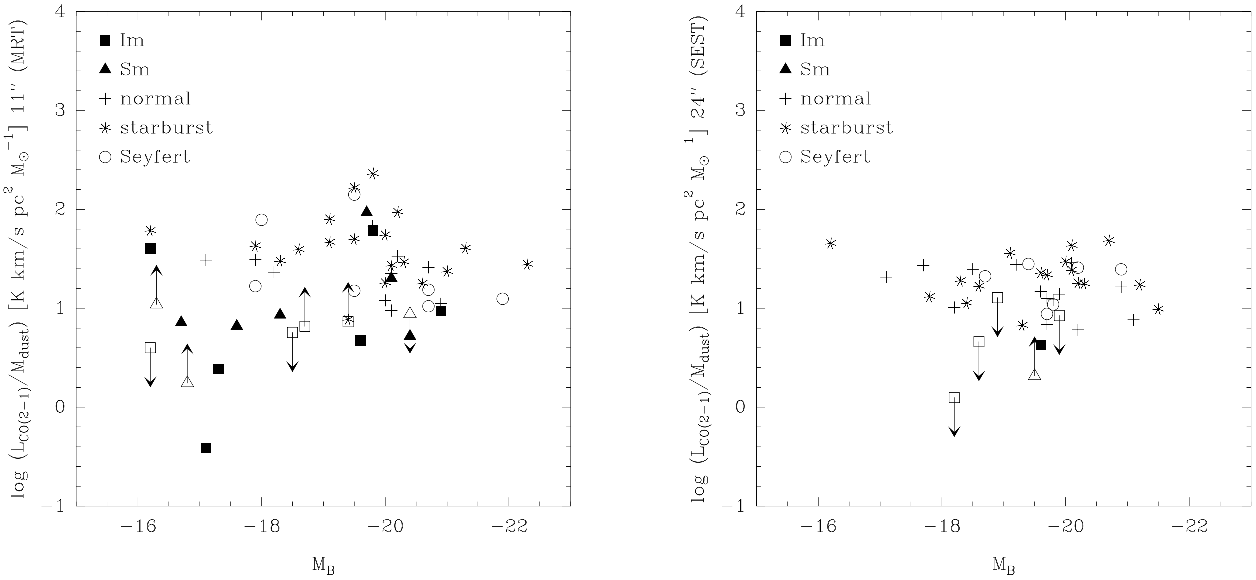

Figure 4: Ratio of CO(2–1) luminosity to dust mass versus absolute blue magnitude. *Left:* MRT data (11″). *Right:* SEST data (24″). Open squares and triangles denote upper/lower limits for Im and Sm galaxies respectively.

4.4 Dust–to–gas ratio

Dust is an important constituent of the ISM as it is –like molecular gas– strongly connected to star formation. The grain surfaces provide a formation site for molecules. Large grains efficiently absorb the UV radiation of young massive stars and re-radiate the energy at longer wavelengths

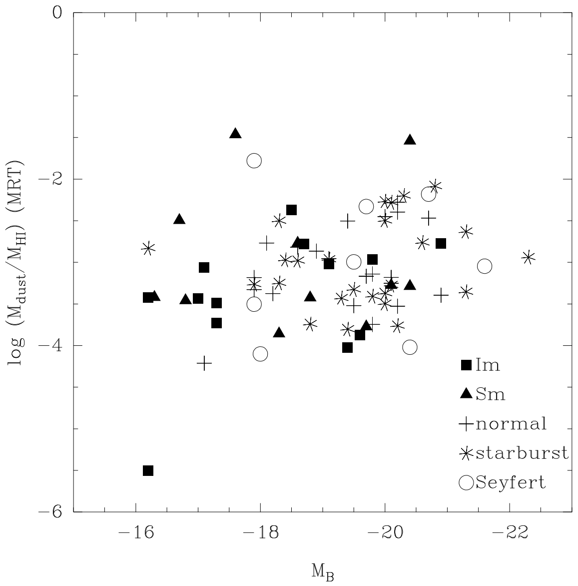

Figure 5: Dust–to–gas ratio versus absolute blue magnitude from MRT data. For the dwarf galaxies multi–channel data are used for the determination of the dust mass whereas the masses of the comparative galaxies result from single–channel data (11″ beam). The dwarf galaxies adopt a mean logarithmic ratio of -3.47 ± 0.79, while for the comparative galaxies we yield -3.02 ± 0.55.

thus reducing the molecular dissociation. The determination of the dust mass allows to study the ratio of dust-to-atomic hydrogen. In Fig. 5 this ratio reflecting the efficiency of dust production is plotted as a function of absolute blue magnitude. As the main constituents of dust –according to the common models– are carbon and silicon, a higher efficiency is supposed for more metal–rich systems. Opposite to the supposed behaviour the galaxies show no distinct dependency on M_{B}. The values for dwarf galaxies are well mixed up with the values for earlier type systems. One explanation may be that the comparison of the samples is not reasonable: The use of multi–channel data for the dwarf sample should result in reliable estimates of the dust temperature and mass. In contrast, the available single–channel data for the comparative galaxies might in some cases lead to an underestimate of the dust mass despite the central concentration. Nevertheless, taking into account only the dwarf galaxies, the ratio of dust–to–atomic hydrogen cannot be dominated by the metallicity alone. As the equilibrium between formation, destruction and outflow of dust is strongly affected by supernovae the star formation history of a galaxy is most probably another crucial parameter influencing the dust–to–gas ratio which has to be taken into account (Lisenfeld & Ferrara 1998). Still, the relationship between M_{B} and metallicity is under debate and future observations should focus on the determination of the relative oxygen abundance as a more reliable indicator for metallicity in the dwarf galaxies observed.

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