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# MILLIMETER OBSERVATIONS OF THE MAGELLANIC CLOUDS

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## ABSTRACT

Millimetric observations (1–2 mm) toward the Magellanic Clouds from Antarctica show a good spatial correlation with the *IRAS* 100 μm emission in the same sky regions. Very likely a cold component coexisting with the warm dust detected by *IRAS* has been observed.

*Subject headings:* galaxies: Magellanic Clouds — radio sources: galaxies

## I. INTRODUCTION

Because of their proximity, the Magellanic Clouds are objects of special interest. Far-infrared observations of these galaxies have shown that these irregulars are not particularly active in the infrared. The LMC has a total far-infrared (10–100 μm) luminosity $L_{IR} \sim 7 \times 10^8\ L_\odot$ and the SMC an $L_{IR} \sim 7 \times 10^7\ L_\odot$ (Schwering 1988), and both show an enhanced gas-to-dust ratio with respect to the Milky Way (Koorneef 1984; Schwering 1988). In the Clouds only regions with high infrared surface brightness show high dust temperature (40–50 K), while the temperature of the diffuse emission is about 25–35 K.

However, the true dust column density cannot be properly estimated only by means of the FIR measurements, since the *IRAS* satellite is not sensitive to dust colder than 20 K and the bulk of dust mass is expected to emit at submillimeter and millimeter wavelengths (Mathis, Mezger, and Panagia 1983). Furthermore, submillimeter and millimeter flux density is a good tracer of the total dust, gas, and molecular mass and could represent an alternative way to estimate these parameters (Thronson *et al.* 1987).

Millimeter observations of extragalactic objects have recently been taken for a small sample of spiral galaxies (Chini *et al.* 1986), for a few active star-forming galaxies (Thronson *et al.* 1987) and for other extragalactic sources (Elias *et al.* 1978). Most of the galaxies with thermal emission present a 1 mm flux much larger than would be predicted by extrapolating their radio spectra (Elias *et al.* 1978). The far-infrared/submillimeter spectra of spiral galaxies have been explained by Chini *et al.* (1986) with the presence of at least two different dust components: a warm one at ~53 K and a cold one at ~16 K. The presence of a cold thermal component seems a natural way to explain also the spectra taken by Thronson *et al.* (1987).

During a run of submillimeter observations from the Italian base in Antarctica (Terra Nova Bay, 74°41′.61 S, 164°06′.89 E), our instrument, devoted to the search for cosmic background radiation anisotropies, was pointed at the Magellanic Clouds and detected their emission at 1 and 2 mm wavelengths.

Our results show that a millimeter excess, with respect to a gray body at 25–35 K with an emissivity proportional to $\lambda^{-1}$ to $\lambda^{-2}$ fitting the *IRAS* 60 and 100 μm fluxes, occurs. The presence of dust colder than that detected by *IRAS* seems a reliable speculation to explain our measurements.

## II. THE OBSERVATIONS

The detailed description of the experimental setup, the calibration of the system together with the procedure of the data analysis can be found in Andreani *et al.* (1988). Here we only report the main characteristics of the instrument.

Two detectors, located in two distinct cryogenic systems, collect the radiation reflected from a plane mirror placed near the focus of a flux collector, 1 m in diameter, which is shaped as an f/2 off-axis paraboloid and defines a ~1° field of view (FOV). The flux collector is tilted at a frequency of 8 Hz and performs a beam switching of 2°.5 in the sky. The oscillation frequency is chosen to lie in a range where the bolometers do not have a frequency-dependent response and are not strongly contaminated by the 1/f noise (see, e.g., Kruse, McGlauchlin, and McQuistan 1963). The frequency and the amplitude are controlled via software by means of a computer system. The telescope does not have any accurate pointing system, and the mirrors may be aligned to look either at the zenith or at most at a few degrees from it. The modulation is performed along the east-west direction.

Two f/4.5 helium-cooled Winston parabolic concentrators, inside the cryostats, provide the matching between the detectors and the optics. Only radiation reflected from the inner part of the mirror falls into the detectors, in order to reduce spurious signals coming from the ground.

The first cryogenic system contains a $^3$He-cooled composite Ge bolometer coupled to a 4 K cooled bandpass mesh, which defines a 500 μm bandwidth around 2150 μm, suitable to match the atmospheric window. The second detector is a Si bolometer, cooled to 1 K and coupled to a low-pass filter with a cut-on around 1000 μm (Mason *et al.* 1986).

By considering the filter transmission, the atmospheric transmission spectrum (see Liebe 1983), and the dust spectrum (assumed to be a thermal emission spectrum whose temperature and spectral index are inferred from the observed intensities), the effective central wavelengths of the two systems are respectively 2090 and 1160 μm.

As far as the calibration of the instrument is concerned, here we stress only that its performance is not constrained by the detector noise, and the measured DC responsivities turn out to be 10 μV K$^{-1}$ at 2 mm and 50 μV K$^{-1}$ at 1 mm (see for further details Andreani *et al.* 1988).

Data from the SMC were collected by pointing the instrument at $\sim 1°$ off the zenith (toward the north), and each independent field of view was observed for about 16 minutes ($\sim 1°$). The scanning of the sky was performed by the Earth's rotation. Data were integrated for 30 s and sampled every 10 s. The observations of the LMC were carried out with the same procedure, during the same day (on 1988 February 8) and gathered by pointing the instrument at 5° toward the north. The observing time for each field of view was about 12 minutes ($\sim 1°$).

The real-time signals from the LMC can be seen in Figure 1. The plot shows 900 data collected in $2\frac{1}{2}$ hr. The signal is compared with that from a simulation of the experiment constructed as follows: the experimental response is obtained by carrying sources with different sizes through a Gaussian-shaped beam and then modulating the source signal with a sinusoidal pattern. The result of this simulation for a 2° source is superposed on the real signal in Figure 1. This allows us to deduce that the detected signal is, very likely, due to a 2° source in the direction of $\alpha \sim 5^h$, $\delta \sim -70°$.

To determine the signal-to-sky noise ratio, the rms value of the sky noise is compared with the signal from the LMC. The latter is $\sim 500$ nV, while the rms sky noise is $\sim 48$ nV; then we estimate a signal-to-noise ratio of $\sim 10$. With regard to the SMC a similar value results from the same comparison.

In order to build independent sky regions, these data must be integrated over a period of time corresponding to a field of view. This average process smooths part of the atmospheric fluctuations, at least the high-frequency ones. The reduced data for the scan of the LMC and the Galaxy are shown in Figure 2. Some of the 1 mm data are missing because of a decrease in the detector sensitivity.

Because of the uncertainty of our pointing system, to check further that the detected signals are signatures of these galaxies, we perform a quantitative comparison with the *IRAS* data: we use and analyze the two fields PL 202 and PL 204 from the original release of the *IRAS* HCON 3 survey by means of the software package developed by Rossi *et al.* (1988). The space resolution of the *IRAS* data is degraded by smoothing the *IRAS* images with a 1° FWHM Gaussian filter, and differential measurements are simulated by subtracting the intensities of two different regions of sky 2°.5 apart.

The comparison between the reduced data and the corresponding *IRAS* data is shown in Figures 3 and 4, where the 100 $\mu$m gradient is shown together with the 2 mm one.

A striking correlation between the two sets of data, for the SMC 83% with a confidence level of 99.5% and for the LMC

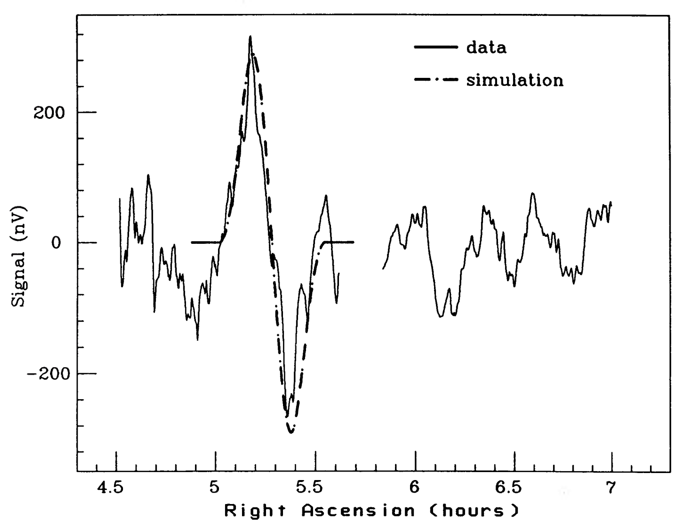


FIG. 1.—Real-time signal from the LMC. Data are sampled each 10 s and integrated over 30 s. A strong signal emerges from the sky noise with a signal-to-noise ratio of $\sim 10$ (see text for details). The dot-dash curve superposed on the LMC signal is a computer simulation of the experiment response to a 2° source. Data are missing between $\alpha = 5.6$ and $\alpha = 5.8$.

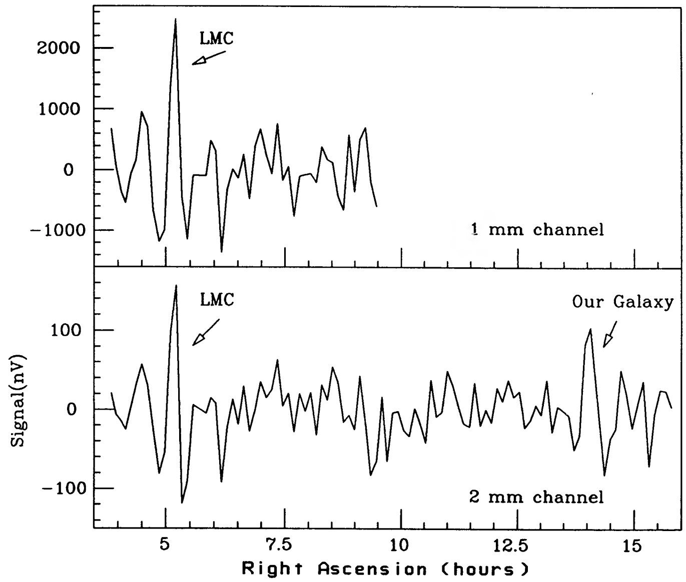


FIG. 2.—Twelve hours of observations including the LMC and a region of our Galaxy at R.A. $\sim 14^h$, de $\sim 70°$. *Upper panel:* 1 mm channel. *Lower panel:* 2 mm channel. The data are already reduced, and the signals are well above the residual atmospheric noise. Data from the Galaxy are missing at 1 mm (*upper part*) because of a decrease in sensitivity due to the He-refilling problem.

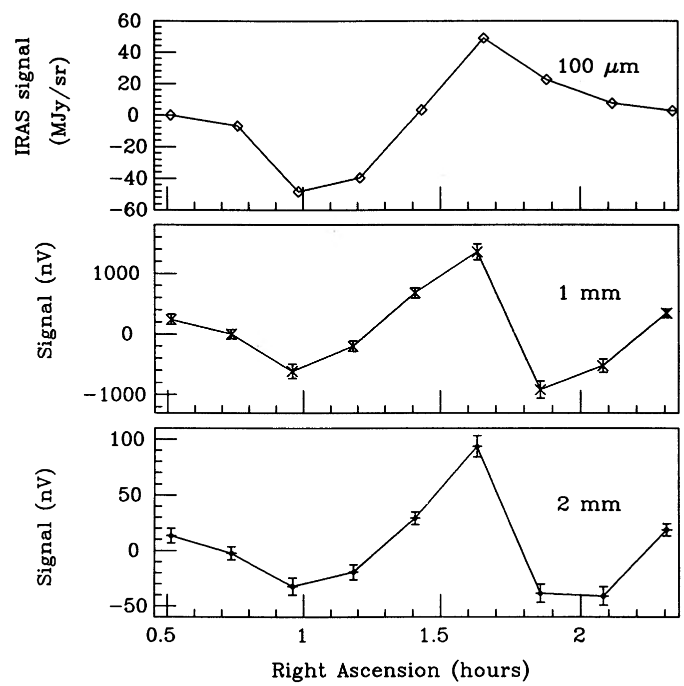


FIG. 3.—Our reduced observations of the Small Magellanic Cloud (*curves labeled 1 mm and 2 mm*) compared with the *IRAS* 100 $\mu$m data for the same galaxy (*curve labeled 100 $\mu$m*).

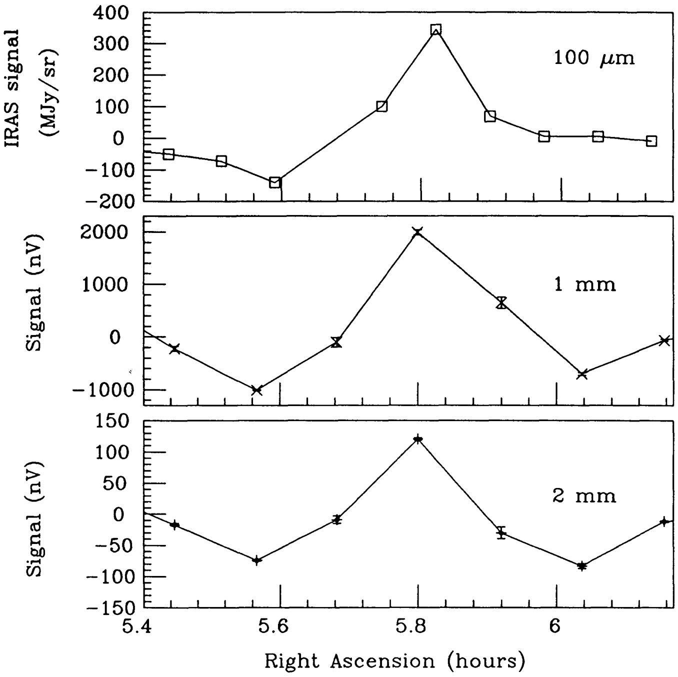


FIG. 4.—Same as Fig. 3, but for the Large Magellanic Cloud

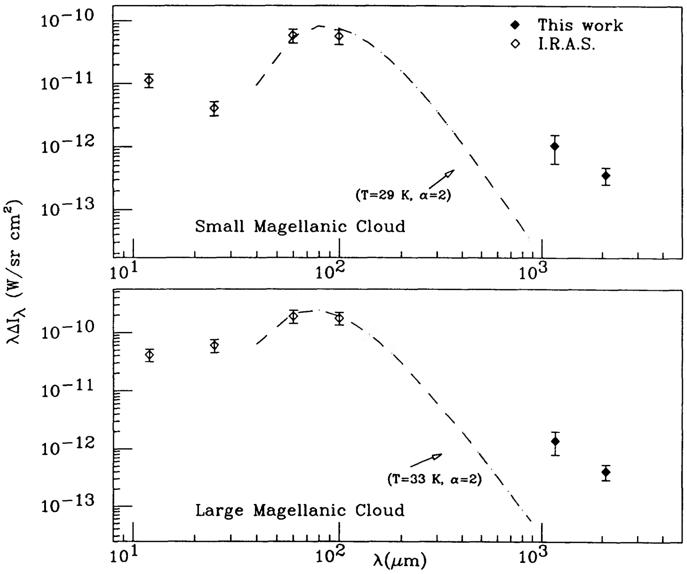


FIG. 5.—Far-infrared and submillimeter spectra of the Magellanic Clouds. The 12, 25, 60 and 100 μm intensities have been obtained by simulating the sky modulation on the *IRAS* high-resolution maps. A gray-body curve fitting the *IRAS* measurements is reported for comparison (see text for details).

74% with a confidence level of 97.5%, provides strong evidence for the detection of the two *IRAS* sources in spite of the huge difference in wavelength.

The spectra are shown in Figure 5. To compare our observed intensities with the infrared spectrum, we correct them for the atmospheric absorption. In fact, by using a simple experimental procedure we measured the atmospheric transmission in each band (Dall'Oglio *et al.* 1988; Andreani *et al.* 1989); the average values turn out to be 90% at 2 mm and 65% through the edge filter (with cut-on at 1 mm).

The error bars are evaluated by taking into account the calibration uncertainties (~20%) and the sky noise (~10% at 2 mm and ~20% at 1 mm). With regard to the 1 mm points, the reported error bars include also the uncertainty on the exact bandwidth of the filter.

## III. DISCUSSION

In Table 1 are reported the parameters inferred from the comparison between the *IRAS* data and our own. In columns (2) and (3) the spatial correlation coefficient and the corresponding confidence level between the *IRAS* 100 μm and the millimetric signals are listed, while in columns (4), (5), and (6) the *IRAS* 100 μm and the observed millimetric fluxes from these two galaxies are reported. As is evident from the 100 μm–1 mm and 100 μm–2 mm ratios, a single temperature dust distribution does not fit the four signals at 60 μm, 100 μm, 1 mm, and 2 mm.

To evaluate whether the thermal and nonthermal radio emission can significantly contribute to the millimetric spectrum, we extrapolate the radio spectra of the Magellanic Clouds reported by Alvarez, Aparici, and May (1987), Mountfort *et al.* (1987), and Loiseau *et al.* (1987). The resulting fluxes are in columns (7) and (8) in Table 1. This contribution to the millimetric points turns out to be negligible in comparison with the detected intensities (cols. [5] and [6]).

Therefore, we try to determine whether our observations provide evidence for thermal emission from cold dust. This can be done in two ways: (1) Following Chini *et al.* (1986), we fit the *IRAS* 100 μm and the millimeter points with a modified Planck spectrum: $\lambda^{-\alpha}B_\lambda(T_d)$, where $\alpha$ is the spectral index of the dust. We find the temperatures and spectral indices listed in Table 2A. The resulting temperature and the calculated 100 μm–1 mm flux density ratios are in good agreement with those predicted by the Chini *et al.* model. (2) On the other hand, if we consider separately the *IRAS* measurements at 60 and 100 μm and the millimetric points, we can fit the data with two thermal components, as suggested by the recent observations of spiral

TABLE 1

MILLIMETER OBSERVATIONS OF THE MAGELLANIC CLOUDS AND COMPARISON WITH *IRAS* 100 MICRON DATA

| | COMPARISON WITH *IRAS* | | OBSERVED FLUXES[a] | | | EXTRAPOLATED RADIO FLUXES[a,b] | |
|---|---|---|---|---|---|---|---|
| CLOUD (1) | Correlation Coefficient (2) | Confidence Level (3) | $F_{100\,\mu m}$ (4) | $F_{1\,mm}$ (5) | $F_{2\,mm}$ (6) | $F'_{1\,mm}$ (7) | $F'_{2\,mm}$ (8) |
| SMC......... | 83% | 99.5% | $8.7 \times 10^5$ | $905 \pm 440$ | $174 \pm 51$ | $1.0 \pm 0.1$ | $0.5 \pm 0.05$ |
| LMC......... | 74% | 97.5% | $4.2 \times 10^6$ | $1220 \pm 530$ | $198 \pm 59$ | $17.7 \pm 2.0$ | $8.0 \pm 0.9$ |

[a] Flux in units of $10^{-18}$ W cm$^{-2}$ sr$^{-1}$ μm$^{-1}$.

[b] Extrapolated fluxes from radio spectra (Alvarez, Aparici, and May 1987; Loiseau *et al.* 1987).

TABLE 2

INFRARED/MILLIMETER PROPERTIES OF THE MAGELLANIC CLOUD SPECTRA

A.

| Cloud | Derived Dust Temperature[a] $\alpha = 1.0$ | $\alpha = 1.1$ | $\alpha = 1.2$ |
|---|---|---|---|
| SMC......... | ~14 | 15–16 | 15–16 |
| LMC......... | ~15 | 17 | 17–18 |

B.

| Cloud | Derived Dust Temperature[b] $\alpha = 1.0$ | $\alpha = 1.1$ | $\alpha = 1.2$ | $T_d$[c] $\alpha \sim 2$ |
|---|---|---|---|---|
| SMC......... | 6–12 | 10–14 | 14 | ~29 |
| LMC......... | 6–13 | 10–16 | 16 | ~33 |

[a] Parameters of the curve $\lambda^{-\alpha}BB(\lambda, T_d)$, fitting the 100 $\mu$m, 1 mm, and 2 mm points.

[b] Parameters of the curve $\lambda^{-\alpha}BB(\lambda, T_d)$, fitting only the 1 mm and 2 mm points.

[c] Based on *IRAS* 60 and 100 $\mu$m observations only.

galaxies at 160 and 360 $\mu$m by Stark *et al.* (1988). In this case we infer rough values for the temperature and the spectral indices of the two components. The temperatures are evaluated once the spectral index is fixed to a value between 1 and 2, as most of the models for dust grains predict (e.g., Draine and Lee 1984). The few values for $T_d$ and $\alpha$ are listed in Table 2B.

For both cases our data seem to confirm the hypothesis of the presence of a cold dust component responsible for the bulk of the millimetric emission. For a dust temperature of ~15–16 K, we find the following values for the optical depths at 1 mm: $\tau_{LMC} = (2.5 \pm 1.1) \times 10^{-4}$ and $\tau_{SMC} = (1.8 \pm 0.9) \times 10^{-4}$. Assuming that the $\tau/N_H$ ratio is the same as that inferred from the Milky Way observations (e.g., Draine and Lee 1984), the evaluated hydrogen column densities are $N_H(\text{LMC}) = 3.7 \times 10^{21}$ cm$^{-2}$ and $N_H(\text{SMC}) = 2.4 \times 10^{21}$ cm$^{-2}$.

## IV. CONCLUSIONS

Millimeter observations of the Magellanic Clouds from Antarctica seem to provide evidence for the presence of a very cold medium coexisting with the warm component sampled by *IRAS*. This result suggests that very likely we have detected the thermal emission from very cold dust, whose temperature cannot be determined reliably only by means of our millimeter points. Our observations could agree with the picture suggested by Chini *et al.* (1986), who have shown that, for a sample of 18 spiral galaxies, the far-infrared and submillimeter integrated spectrum can be fitted with at least three dust components: cold dust with temperature ranging between 14 and 25 K associated with the neutral and molecular hydrogen heated by the general interstellar radiation field; a warm dust with temperature of 30–50 K, located in H II regions and dense molecular cloud cores heated by O and B stars; and a hot dust (a few hundred K) due to very small grains emitting in the near-IR.

However, more observations of the submillimetric and millimetric spectra are required in order to establish the nature of these results.

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