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Research Note

2mm observations of the Large Magellanic Cloud at 5′ resolution

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Abstract. We report on new millimetric continuum observations of the Large Magellanic Cloud (LMC) made from the Italian Base in Antarctica with a 2.6 metre diameter telescope. The telescope scanned two strips at constant declinations -69° and -69.16° across the entire source with an angular resolution of 5 arcminutes. The comparison of the mm wavelength observations with radio, CO and FIR measurements suggests that most of the observed mm emission is thermal and can be associated with very cold dust present in the molecular clouds of this Galaxy. The dust properties inferred from these observations are briefly discussed.

Key words: galaxies: Magellanic clouds – ISM: clouds – radio continuum: interstellar – dust, extinction

1. Introduction

As our nearest neighbours the Magellanic Clouds (MCs) represent a unique 'laboratory' to test astrophysical processes occurring in galaxies distinct from our own. Moreover, the difference in morphology, age, metallicity from our Galaxy make observation of these sources unique in furthering our understanding of stellar formation and evolution in less evolved environments.

It is well-known that IR measurements, such as those performed by the IRAS Satellite, are fundamental in addressing issues related to the properties of interstellar grains and their catalytic role both in star-forming regions and molecular clouds. The star formation activities in galaxies will be clearly evident through the measurement of enhanced FIR emission from the heated dust in the galaxy's interstellar medium, ISM. A measurement of the dust distribution in external galaxies will allow us to understand both the evolution of the dust and its role in star formation activities. Although FIR measurements are good tracers of warm dust, they are not sensitive to dust colder than 20 K, the temperatures expected for the bulk of grains in a galactic ISM. To determine the total amount of cold dust and its distribution we therefore need to make longer wavelength, sub-mm or mm, measurements. Further, in making observations at such long wavelengths, we expect that a more reliable estimate of the dust temperature and mass can be determined because of the slow variation of the dust temperature with the absorbed power ($T_d \propto P^{0.2}$).

A major obstacle to ground-based observations at mm wavelengths is the variability of the generally poor atmospheric transmission at all but the highest and driest sites. Here we report measurements made from the Italian base in Antarctica which provides a clean and stable atmosphere with a low level of water vapour making it an ideal site to carry out good sub-mm and millimetric photometry (see e.g., Dall'Oglio et al. 1988). From this site we have made a series of ground-based observations of the millimetric continuum emission of our Galaxy and the Magellanic Clouds (Dall'Oglio & de Bernardis 1988; Andreani et al. 1990; Andreani et al. 1991a; Andreani et al. 1991b) over several observing seasons. We made the first detection of the 1 and 2 mm continuum emission from both the MCs with a 1 metre diameter flux collector (Andreani et al. 1990). The large beam of this telescope ($\sim 1°$) resulted in a measurement of the global emission only. However, we were able to demonstrate that a good spatial correlation existed between the 100 μm and mm continuum emission. This result together with the fact that the mm fluxes obtained were much larger than those predicted

Send offprint requests to: P. Andreani from a simple extrapolation of either the radio or FIR spectra of these galaxies, led us to conclude that the mm continuum flux must be dominated by the thermal emission from cold, 15-18 K, dust.

In this paper we present new 2 mm continuum observations of the Large Magellanic Cloud obtained at higher spatial resolution (5 arcmin) with a ^{3}He-cooled photometer at the focus of a 2.6 metre telescope. The data show that millimetric continuum emission is present in the substructure of this Galaxy and appears to be associated with the molecular clouds. The observations are reported in Sect. 2, whilst the results and discussion on the cold dust properties and spatial distribution are given in Sect. 3.

2. The observations

The new 2 mm observations of the LMC were made during the antarctic summer 1990-1991 with the O.A.S.I. (*Osservatorio Antartico Sub-millimetrico Infrarosso*) 2.6 metre telescope. The telescope, a Cassegrain system with both mirrors made of an aluminum alloy, is supported on an altitude-azimuth mount. Beam-switching is achieved by modulating the secondary mirror. The FWHM beamwidth is 5′ and the beam separation is set at 16′. The photometer uses a ^{3}He-cooled Si-composite bolometer fed via a Winston cone. Wavelength selection is effected by a multi-layer metal mesh bandpass filter centered at 2 *mm* which spectrally matches the atmospheric transmission window. The detector signal was integrated at the output of the lock-in amplifier for 3 seconds before being stored by a PC based data aquisition system which sampled the output every second. A more detailed description of the telescope and photometer can be found in Dall'Oglio et al. (1991) and Dall'Oglio et al. (1992).

For the observations of the LMC a drift-scan technique was used: the telescope was kept at fixed coordinates (corresponding to a fixed LMC declination) and the galaxy was scanned via the Earth's rotation. Since the latitude of the site is high and the observations were made close to the source transit, the chopped beams follow closely a path of constant RA with negligible rotation evident over the observation period. This simplifies the data analysis in that we can justifiably co-add sequential scans. The observations reported here were taken on two separate days. On the first day several scans were obtained in quick succession by repositioning the telescope to the designated declination whilst incrementing the RA ahead of the source and then waiting for the LMC to transit through the telescope beam as the Earth rotated. During the second observing day only one transit was recorded. A somewhat different analysis technique was used for the two cases.

(1) All the data within particular beamwidth (FOVs), referring to the same RA range (declination was kept constant), were averaged to give single values. This resulted in the scan shown in Fig. 1a for -69° declination . Note that each point corresponds to a total integration time of 130 seconds and that the scan represents ON-OFF (beam-switched) measurements, i.e. a measurement of the *gradient* of the mm emission. The dashed lines correspond to $\pm\,3\sigma$ error bars, where the standard error σ has been estimated by adding quadratically the sky and the detector noise: $\sigma = \sqrt{\sigma^2_{sky} + \sigma^2_{det}}$. An estimation of the detector noise integrated over each point gives that $\sqrt{\sigma^2_{det}} < 3.1$ nV, while a very conservative value for the magnitude of the sky noise is given by the variance of the entire scan, i.e. that consisting of sky noise plus the source emission (and detector noise).

(2) In this case, since only one scan was available, the high frequency atmospheric noise was filtered using the Savitzky-Golay algorithm (Press & Teukolsky 1990). This smooths the data with a bin size equal to the beamwidth (note that for the Earth rotation at the OASI latitude it takes ~75 seconds to cover 5 arcminutes in the sky, so there are 75 data points in each FOV bin). A low order (2^{nd} or 3^{rd}) polynomial fitting was applied to the scan, to take into account the small drift of the system and the low frequency variations in atmospheric emission during the observations.The result is shown in Fig. 2a (limited to the 4.6-6.2 hours RA range at the fixed declination of -69.16°). Again the dashed lines correspond to $\pm 3\ \sigma$ error bars, estimated from the variance of the entire scan plus that of the detector noise (cf. above).

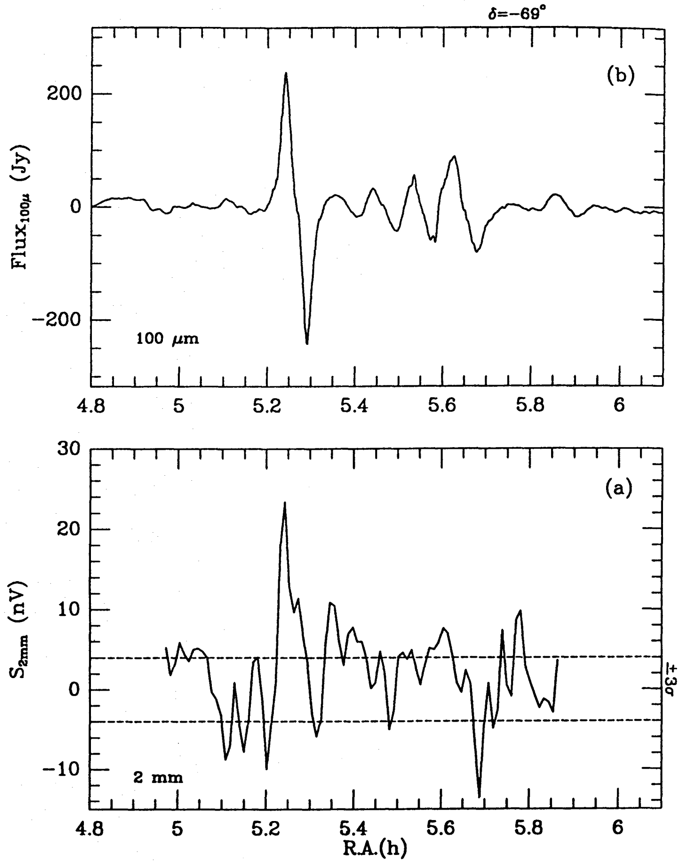

Fig. 1. a A scan of the LMC at -69° declination at 2 *mm* taken with the 2.6m telescope. The FWHM is 5′. **b** The IRAS 100μm scan of the same sky region determined from a simulation of our experiment using the IRAS data base. The conversion factor for the 2 mm signal is 0.2Jy/nV

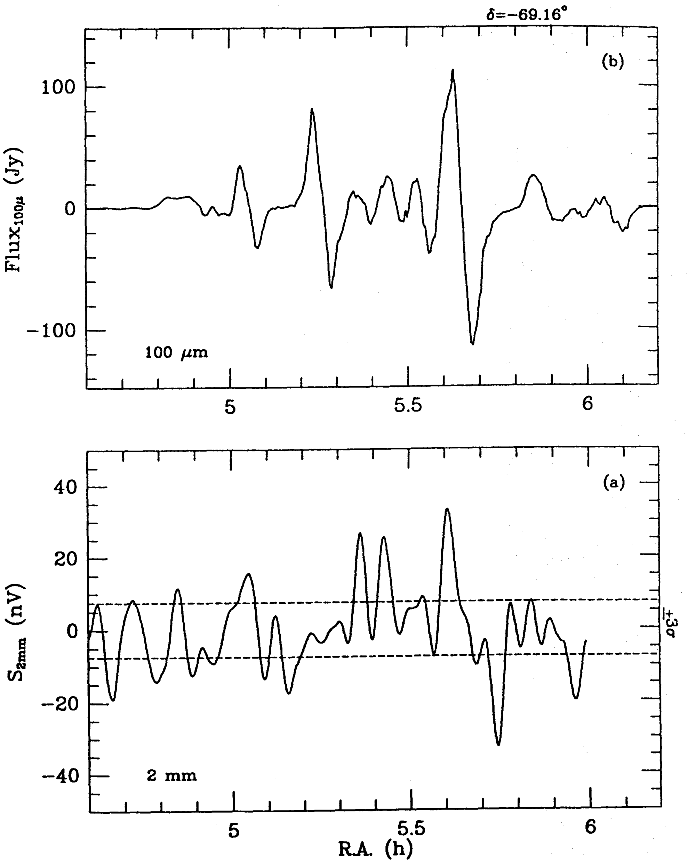

Fig. 2. a Another scan of the LMC at -69.16° declination at 2 mm. **b** The IRAS 100μm scan of the same region. The overall spatial correlation is statistically significant and it turns out to be of 0.3, while for the signal at $5.6^h \rightarrow 5.8^h$ the correlation coefficient is 0.5. The conversion factor for the 2 mm signal is 0.2Jy/nV

In this case the detector noise integrated over 75 seconds is 4.6 nV.

The longer integration time achieved via of the first observational strategy produces lower values for the instrumental plus atmospheric noise but is subject to systematic effects relating to the continual re-positioning of the telescope. This is contrasted with the second observational procedure which results in higher noise for each data point but with minimal systematic effects.

The atmospheric transmission was evaluated using models based on the vertical distribution of the atmospheric constituents obtained from radiosonde measurements which were kindly provided by the *Divisione Ambiente Atmosferico, ENEA-AREA AMBIENTE*. The astronomical flux scale was determined from observations of Venus, Saturn and the Moon, being the only observable objects in the sky during the campaign. Details of the calibration procedures are reported in Dall'Oglio et al. (1992). For this data we have used the calibration scale determined using the Moon since both the Moon and the LMC completely fill the telescope beam, whilst Venus and Saturn do not. Further, this choice of a relatively bright calibration source allows us to quantify any low level side-lobe effects. The voltage to flux conversion factor for the 2 mm peak-to-peak signal shown in Fig. 1a and Fig. 2a is 0.2 Jy/nV.

3. Results and discussions

3.1. Origin of the detected signals

The interpretation of earlier measurements of the mm continuum emission were ascribed largely to thermal emission from very cold dust grains (Andreani et al. 1990). However, it is likely that part of the measured flux arises from free-free and/or synchrotron emission. To better determine the nature of the observed emission we have made comparisons between the data from this work and measurements of the same sky regions at FIR (A), radio (B) and CO (C) wavelengths.

(A) IRAS data have been used to check whether the mm flux is spatially correlated with known FIR sources. In order to do this, we used the IRAS high resolution 100 μm map and simulated the expected signals from a beam-switched photometer with our beamsize scanning through the source (see also Andreani et al. 1990). The 100 μm IRAS map fluxes were averaged with a gaussian-shaped beam with FWHM of 5 arcmin. Then, each 5 arcmin FOV was subtracted from its companion 16 arcmin along the -69° or -69.16° declination. The 100 μm simulated beam-switched signal is shown together with the measured 2 mm signals in Figs. 1b and 2b respectively.

The main feature of Fig. 1a can be clearly associated with the nebula N105 which corresponds to the IRAS cloud # 534 in the list published by Schwering (1988). The ratio between the 100 μm and 2 mm fluxes in Jys, $\frac{F_{100\mu m}}{F_{2mm}}$, turns out to be of ~ 50. Another feature in the 2 mm data, which appears to be related to a feature seen in the 100 μm map, is that at RA = 5.6 *h* whose $\frac{F_{100\mu m}}{F_{2mm}}$ ratio is ~ 20. However, since this detection is marginal this feature could be as cold as the first one.

The main feature seen at RA = 5.6 $\rightarrow$ 5.8 *h* in Fig. 2a (coincident with the 30 Dor region) has the positive peak of the differential signal coinciding with that expected for a known IRAS source but it has the negative one which is offset from the expected one (the correlation coefficient with the 100 μm scan turns out to be greater than 0.5). It is likely that the cold dust (that traced by the mm emission) has a larger spatial extension with respect to that of the warm dust (traced by the 100 μm However, we cannot a priori exclude that some unknown systematics make this detection a marginal one. In addition to this main feature at RA = 5.6 $\rightarrow$ 5.8 *h* other features are present in the longer wavelength scan which show up outside the 3σ confidence limit. It is not necessarily sensible to connect these latter features to the 100 μm emitting regions as they could be associated with other interstellar material. The strong FIR feature at RA = 5.25 *h* is not seen at 2 mm. but it is likely that the feature at RA = 5.05 *h* which shows up in both mm scans is real. The overall spatial correlation between the 100 μm and 2 mm scans across this feature is 0.30 with a confidence level higher than 99.9 %.

(B) Radio maps and spectra of the LMC have been published by Alvarez et al. (1987), Mountfort et al. (1987) and Klein et al. (1989). The latter authors have fitted the radio spectrum for different regions using both thermal (free-free) and non-thermal components. They also argue that the evident similarity between the radio (1.4 GHz) and 100 μm maps of the LMC suggests that most of the radio sources have a FIR counterpart.

To quantify the thermal and non-thermal radio emission contributing to the detected 2 mm fluxes, the radio spectra of the two sources spatially correlated with sources in both the radio and FIR maps have been extrapolated to a frequency of 150 GHz (2 mm). The extrapolation gives negligible contribution in one case (RA = 5.2 h, Fig. 1a) and for the other cloud (R.A.=5.8 h, Fig. 2a) the maximum allowed radio emission is 30 % of the detected flux.

(C) Since most of the detected emission is likely to originate from cold dust which largely resides in the galactic molecular clouds, the most interesting comparison is that with the CO map of the LMC. Since our spatial resolution is 5′ we have used for comparison the CO maps published by Cohen et al. (1988) and those by Garay et al. (1993) which have 8′ resolution. The features seen at RA = 5.2 h in Fig. 1a and at RA = 5.65 h in Fig. 2a are seen to be directly associated with the CO clouds observed in these regions.

3.2. *Dust properties*

In the following discussion we assume that the most likely hypothesis for the mm signal is that it is mainly thermal and due to emission from cold dust grains. We can then use the present measurements together with those of IRAS and CO data to constrain the physical properties of the dust grains.

We assume that the good spatial correlation between 2 mm and 100 μm data means that both emissions are due to the same dust component and that at long wavelengths the LMC is optically thin.

The inferred mean dust temperature varies according to the assumed dust emissivity. If the dust consists mainly of graphite and silicates the wavelength dependence of the emissivity is $\epsilon \propto \lambda^{-2}$ and the resulting temperature turns out to be 11 →14 K, while dust made of amorphous carbon has a shallower wavelength dependence ($\epsilon \propto \lambda^{-1}$) and higher equilibrium temperature (18 → 22 K). These values together with the prescriptions given by two different models for the interstellar dust (Draine & Lee 1984 (D-L); Mathis & Whiffen 1989 (M-W)) are used to infer dust and gas masses for the regions (whose size corresponds to a FOV) detected at 2 mm and 100 μm. We then compare the gas masses with those found by means of CO observations. However, since dust models fit the dust properties of the Galaxy and these ones could be different in the LMC, some assumptions are needed. Following Pei (1992) we assume that the differences found in the measured extinction curve with respect to that of our Galaxy (namely, higher extinction at short wavelengths with a less pronounced bump at 2200Å) can be ascribed mainly to difference in relative abundance of graphite and silicate grains while leaving their optical properties unchanged with respect to those used to fit the Galaxy extinction curve. However, the gas-to-dust mass ratio has been increased with respect to the Galactic value by a factor of 4 (Koorneef 1982).

Table 1. Dust and gas masses (in $M_\odot$)

Position in RA	M_{dust}	M_{gas}	*dust model*	$M^{\star}_{gas}$
$5^h\ 11^m$	1.1 10^4	4.2 10^6	M-W	2.0 10^6
$5^h\ 11^m$	4.4 10^4	7.0 10^6	D-L	
$5^h\ 38^m$	1.7 10^4	6.2 10^6	M-W	5.6 10^6
$5^h\ 38^m$	7.0 10^4	1.0 10^7	D-L	

* from CO data (Cohen et al. 1988) M-W: Mathis & Whiffen 1989; D-L: Draine & Lee 1984

Table 1 gives the computed values for the dust mass and the gas mass, for the clouds at RA = 5.65 and 5.2 h, using the prescriptions described above. These values are to be compared with the gas masses found from CO line measurements, also given in Table 1. A gas mass of 3.4 10^5 $M_\odot$ and a virial mass of 4.4 10^6 $M_\odot$ has been also estimated for the cloud at $5^h\ 38^m$ by Garay et al. (1993).

The rough agreement between the gas masses inferred from our observations and those found from the CO spectroscopy is probably only fortuitous because of the large uncertainties involved in both methods: the CO line estimation of gas mass is affected by the poor knowledge of the conversion factor between CO line intensity and H_2 column density mainly in an environment with a low abundance of heavy elements. Garay et al. (1993) have, in fact, shown that for the 30 Doradus region of the LMC the CO brightness is significantly weaker than those of Galactic molecular clouds of comparable sizes and that the N(H_2+2H)/CO ratio is ~ 2 larger than the average value for LMC clouds. The same can be true for the dust-to-gas ratio which appears to be a function of the heavy elements abundance (see e.g., Issa et al. 1990; Sodroski et al. 1994; Andreani et al. 1995) and for the grain opacities at long wavelengths which are still poorly constrained by *submm* and mm observations.

We are pursuing our efforts in two directions: further data are being collected with the O.A.S.I. telescope with a double-channel photometer working at 1 and 2 mm simultaneously and a better understanding of cosmic dust properties is currently underway: data on hydrogenate amorphous carbon containing randomly oriented graphitic islands have provided a better match with the observed long wavelength galaxy spectrum (Merluzzi et al. 1994). Therefore, models which properly consider the presence of these materials in the galactic ISM could provide a much better fit to the observed data.

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