High resolution sub–millimetre mapping of starburst galaxies: Comparison with CO emission

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Abstract

We present first results from a programme of submillimetre continuum mapping with the JCMT of starburst galaxies, and comparison of their dust and CO emission. This project was prompted by surprising results from our first target, the nearby starburst M82, which shows in the dust continuum a morphology quite unlike that of its CO emission, in contrast to what might be expected if both CO and dust are accurately tracing the molecular hydrogen. Possible explanations for this striking difference are discussed. In the light of these results, the programme has been extended to include sub–mm mapping of the nearby, vigorously star forming spirals, M83 and Maffei 2. The latter we have also observed extensively in CO, in order to study excitation conditions in its central regions.

Introduction

An important step towards an understanding of of star formation in galaxies would be the ability to accurately determine the mass and distribution of available raw material (mostly H_2) in molecular clouds. The two commonest methods utilise tracers of the H_2 – either rotational transitions of the CO molecule, or sub–mm continuum emission from dust re–radiating the stellar UV. Recently, doubts have arisen over the reliability of these methods as applied to extragalactic molecular clouds, particularly in the extreme environments of 'starburst' galaxies, where vigorous star formation may significantly influence conditions in the clouds (*e.g.* Maloney & Black 1988). If the CO and sub–mm emission are both reliably tracing H_2 we may expect their morphologies to be similar. We tested this by sub–mm mapping of M82, a 'classic' starburst galaxy, and comparison with existing CO observations.[2] The results demonstrated an urgent need for more high resolution sub–mm maps, and detailed study of the excitation conditions of the CO, and the programme has been extended to include M83 and Maffei 2.

Results & Discussion

(i) M82

The central $40''$ x $40''$ of M82 was mapped at $450\,\mu$m in the dust continuum, using the 15–m James Clerk Maxwell Telescope on Mauna Kea, Hawaii, with a beamsize at $450\,\mu$m of $13''$.

Our $450\,\mu$m map is presented in Fig. 1a. Fig. 1b, to the same scale, shows the ^{12}CO J=1–0 interferometer map of Lo *et al* (1987). There is a significant morphological difference between the two maps. The ^{12}CO map shows two distinct peaks, $25''$ apart, either side of the dynamical nucleus ($2.2\,\mu$m peak). This dual peak structure has been interpreted as a 400 pc molecular 'ring' enclosing the starburst (Nakai *et al* 1987). In constrast, our sub–mm map shows only one peak, situated *inside* the 'ring', $\sim 7''$ SW of the nucleus. We believe that the difference is real, and not a result of poor resolution or pointing.

The integrated flux density from our map is 49 ± 21 Jy. Using the equations of Hildebrand (1983), and Gear (1988), with an adopted dust temperature of 47 K (Hughes *et al* 1989), we confirm that the sub–mm

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emission is optically thin, and derive a total gas mass in the mapped region of $(2.0 \pm 0.8) \times 10^8$ $M_\odot$.

The difference in morphology between the CO and sub–mm maps is surprising if, as is commonly assumed, the CO and dust continuum are both reliable tracers of the molecular hydrogen. Our 450 μm map shows similar morphology to 800 μm and 100 μm observations (Hughes *et al* 1989, Joy *et al* 1987). The 450 μm and 100 μm peaks are close to a region of vigorous star formation $10''$ SW of the nucleus. A possible explanation of the differing morphologies, then, is that two dust lobes are present, but are 'swamped', due to enhanced dust temperature, by emission from this region. However, from comparison of 100 μm and 40 μm profiles of M82 (Joy *et al* 1987) we infer no temperature variations greater than $\sim \pm$ 5 K over the central regions, too small to 'fill in' the central depression seen in the ^{12}CO J=1–0 map. Therefore we believe it likely that the sub–mm is tracing predominantly column density variations.

If the dust continuum is accurately tracing the H_2 , then some process must be enhancing the CO emission in the lobes or depressing it in the interior. The integrated intensity of CO emission, I_{CO}, is critically sensitive to conditions in the molecular clouds. Large–beam ^{12}CO J=2–1, ^{12}CO J=1–0 and ^{13}CO J=1–0 observations suggest that the ^{12}CO emission in M82 may be at least partially optically thin, quite unlike Galactic clouds (Knapp *et al* 1980, Stark & Carlson 1982). The situation in M82 is far from simple, however. A recent ^{13}CO J=2–1 map (Fig. 1c) displays a large central peak, spatially coincident with our 450 μm peak and the SW star forming region, which dominates over the two peaks of the 'ring'. As ^{13}CO is usually optically thin, the ^{12}CO/^{13}CO ratio traces changes in ^{12}CO optical depth. The morphology of the ^{13}CO map therefore suggests significant optical depth variations across M82 (Loiseau *et al* 1988).

I_{CO} is also sensitive to changes in CO excitation temperature. One factor which could have a marked effect on the gas temperature is the presence of intense UV fields. H53α measurements of M82 (Fig.2, Puxley *et al* 1989) imply a UV field 10^3 times that in the solar neighbourhood. In such an intense field, the CO may originate from warm (100 K), dense (10^3 cm^{-3}) photodissociation regions at the interface between HII regions and molecular clouds, where the gas temperature greatly exceeds the dust temperature (*e.g.* Tielens & Hollenbach 1985). The existence of such photodissociation zones in starburst galaxies is implied by the detection of 158 μm [CII] emission from M82 and other systems (Crawford *et al* 1985, Stacey *et al* 1989).

(ii) M83 and Maffei 2

It is apparent from the above results that CO and dust cannot both be accurately tracing H_2 across the central regions of M82. It cannot be assumed that M82 is unique in this, indeed, as it seems likely that the CO emission is strongly affected by the vigorous nature of the star formation in M82, it is clear that detailed knowledge of excitation conditions in other such 'starburst' galaxies are required for the correct interpretation of CO data and line ratios. We have therefore extended our study to two other IR– and CO–bright starbursts, M83 and Maffei 2. We have mapped M83 and Maffei 2 at 800 μm in the dust continuum with the JCMT (resolution $16''$). Additionally, we have obtained high resolution observations of Maffei 2 in the J=1–0 and J=2–1 transitions of both ^{12}CO and ^{13}CO , using the IRAM 30–m and Nobeyama 45–m telescopes (Smith *et al* 1989). Observations of two transitions in each of the two commonest isotopes of CO enables us to get a good handle on excitation and optical depth variations across the starburst regions, while the 800 μm mapping is invaluable as an independant tracer of the molecular gas and a test of the reliability of the CO morphology.

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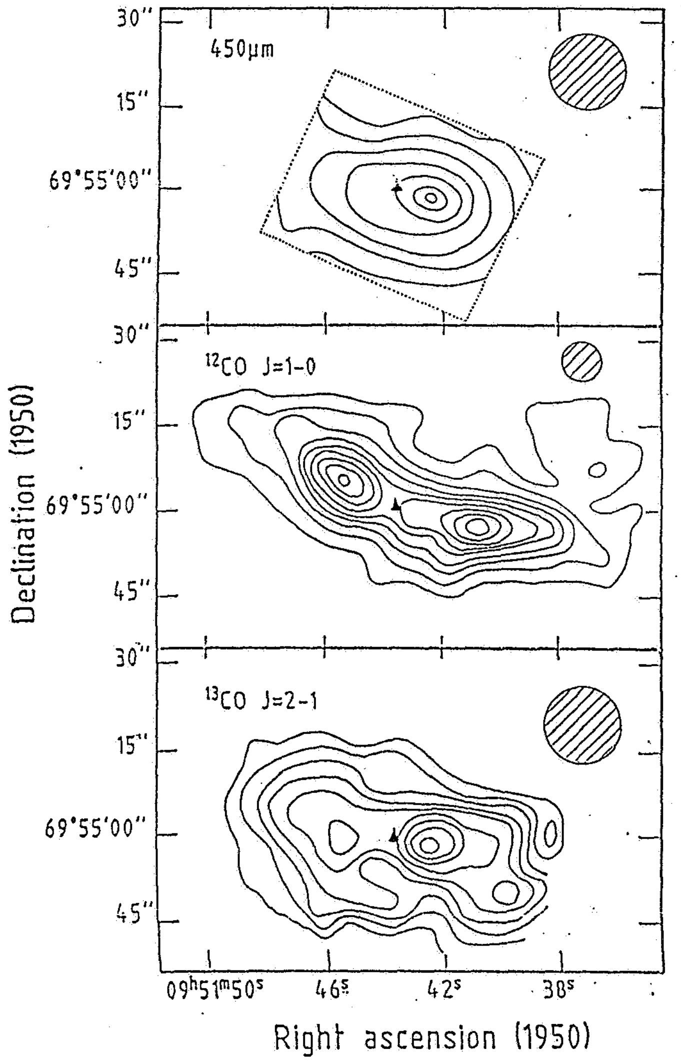

Figure 1

a) 450 micron map of M82, 13" resolution (Smith et al 1989, MNRAS, submitted).

b) ^{12}CO J=1-0 interferometer map of M82, beamsize 7", taken from Lo et al (1987).

c) ^{13}CO J=2-1 map of M82, beamsize 13", from Loiseau et al (1988).

The solid triangle marks the position of the 2.2 micron nucleus.

Figure 2

H53α profile, measured with a 41" beam. From Puxley et al (1989).