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Research Note

Millimeter continuum observations of the active star-forming core of M82

H.A. Thronson, Jr.[1], C.K. Walker[2], C.E. Walker[2], and P. Maloney[3,4]

[1] Wyoming Infrared Observatory, Box 3905, University of Wyoming, Laramie, WY 82701, USA
[2] Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
[3] Department of Planetary Sciences, University of Arizona, Tucson, AZ 85721, USA
[4] Sterrewacht Leiden, Postbus 9513, NL-2300 RA Leiden, The Netherlands

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Summary. We present and discuss a small map of the 1.3 mm continuum emission from cool dust in the central "starburst" region in the peculiar galaxy M 82 (NGC 3034). With the 33″ beam of the NRAO 12 m telescope, the source appears to be less than about 45″ in extent and centered on the region of brightest infrared emission. The total flux density at this wavelength is 1.3 ± 0.3 Jy, where the uncertainty is our estimate of all sources of error. No more than 0.4 Jy of this emission is contributed by thermal and non-thermal gas emission. The molecular hydrogen mass, derived under the assumption that the material in emission in M 82 is similar to that in the disk of the Milky Way, is $3\ 10^8\ M_\odot$, with an uncertainty due to measurement of ±30%. We emphasize the importance of including effects of metallicity in estimations of the H_2 mass and suggest an approximate correction to masses derived from long-wavelength photometry, if the heavy element abundance is different from that of the solar neighborhood. In the case of M 82, such a correction reduces the derived mass to $M(H_2) \approx 1\ 10^8\ M_\odot$. We discuss the uncertainties in estimating H_2 masses from observations of dust continuum emission.

Key words: galaxies: individual (M 82, NGC 3034) – infrared spectra – radio continuum

1. Introduction

The peculiar galaxy M 82 is one of the best-studied objects in the sky, primarily because it exhibits some of the more bizarre characteristics of large-scale star formation. In particular, the galaxy has become a prototype for the class of "starburst" galaxies, a slippery term that usually implies a short-lived period of very active star formation. Rather than describe the very numerous observations of infrared and radio emission from the core of this galaxy, we refer the reader to the recent extensive discussions by Seaquist et al. (1985), Lo et al. (1987), Joy et al. (1987), Klein et al. (1988), Kronberg (1988), Sofue (1988), and Telesco (1988).

The interstellar medium in M 82 has been studied in increasing detail over the past few years. Jaffe et al. (1984) found 400 μm continuum emission from cool dust concentrated to a region less than about 40″ in diameter and centered upon the bright radio and infrared core of the galaxy (see also Elias et al., 1978). About the same time, Young and Scoville (1984) published a large-scale map of the $J = 1 \rightarrow 0$ CO emission from the galaxy, with the brightest region of molecular line emission close to the sub-millimeter continuum peak (see also Knapp et al. 1980; Sutton et al., 1983; Olofsson and Rydbeck 1984; Sofue 1988). There is a major disagreement in that the molecular gas masses derived by Jaffe et al. and by Olofsson and Rydbeck are at least 4 times smaller than that calculated by Young and Scoville. This factor is larger than the uncertainty often attributed to the adopted technique. Lo et al. (1987) mapped the small-scale distribution of the CO emission and derived an H_2 mass in agreement with that of Jaffe et al. and Olofsson and Rydbeck. An accurate estimate of the H_2 mass is important in understanding the extremely high rate of star formation that seems to be taking place in M 82. For that reason, we mapped the millimeter-continuum emission from cool dust presumably mixed with the molecular gas in an attempt to estimate $M(H_2)$ with a technique independent of that used with the CO line observations. Although this is a short note, because of the unusual amount of attention given to M 82, we feel obliged to describe in some detail the uncertainties in estimating $M(H_2)$ from observations of the dust emission.

We have produced a coarse, low-resolution map of the 1.3 mm continuum emission from the active star-forming core of M 82. We shall argue that our technique produces the most reliable results that are presently available, when the uncertainties are fairly considered, with relatively straightforward corrections possible for objects with heavy element abundances much different from that of the Milky Way.

Send offprint requests to: H.A. Thronson, Jr.

2. Observations and data reduction

The infrared-bright center of M 82 was observed during the second week of 1987 January, using the 12 m NRAO [1] telescope on Kitt Peak in Arizona. A Schottky diode heterodyne system was operated in continuum mode at 1.3 mm with a bandwidth of 600 MHz and was offset in frequency to avoid the strong $J = 2 \rightarrow 1$ CO line at 230 GHz. At the wavelength of observation, the telescope half-power beamwidth was found to be 33″ and its shape was nearly gaussian. We estimate the pointing accuracy to be 7″ ($1\,\sigma$ rms).

Atmospheric extinction was determined by tipping the telescope during the observations and typical optical depths were found to be 0.1. We used Jupiter, Saturn, Venus, and 3 C 84 as absolute calibration for which we took brightness temperatures of 165 K, 140 K, and 317 K, respectively, for the planets and $F_\nu = 11$ Jy for 3 C 84. The data were corrected for the size of the planets. Using different calibrators, we found agreement in the observed flux density from the peak of M 82 to about ±15% ($1\,\sigma$ rms). Figure 1 shows the 11 points that we observed, where the quoted uncertainties are internal only and do not include systematic calibration uncertainties. In our map we followed the major and minor axes to determine distribution of interstellar material in the galaxy. However, the emission appears to be less, or only slightly larger, than our beam size, but this is indefinite primarily because of the relatively large uncertainties in pointing: the source appears to be less than about 45″ in diameter. This size is consistent with observations at 58 µm (Telesco and Harper, 1980), 400 µm (Jaffe et al.), and recent interferometric CO line maps (Lo et al., Sofue, 1988). The uncertainty in the total flux density from the map is due primarily to the poorly-known beam shape, in addition to the pointing, but we estimate that 1.3 ± 0.3 Jy is accurate, where the quoted uncertainty includes the full range of the effects of all sources of error.

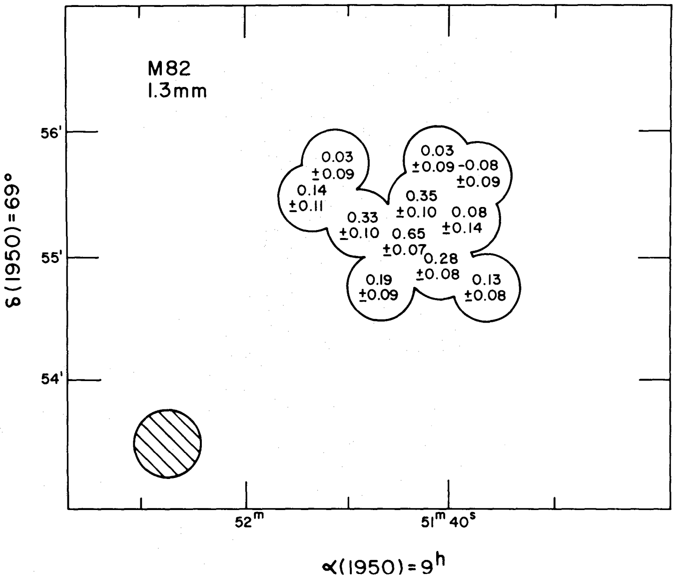

Fig. 1. The distribution of 1.3 mm continuum emission from the center of M 82. Partial circles equal in diameter to the FWHM of our beam are drawn at the 11 positions that we observed and enclose the observed flux density at the position plus the $1\,\sigma$ rms uncertainty (internal errors only). A hatched circle shows the FWHM diameter of the NRAO beam. The major axis of the galaxy is oriented along a position angle of 115° and we followed the galaxian axes for most of the positions of our map. Within the absolute positional uncertainties, the peak of the 1.3 mm emission is coincident with the infrared and molecular line maximum (Rieke et al., 1980; Telesco, 1988)

A potential systematic uncertainty in the following analysis is the contribution from free-free or synchrotron emission to the observed flux density at 1.3 mm. For example, Jura et al. (1978; see also Carlstrom, 1988) reported a flux density of about 0.5 Jy at about 90 GHz, which suggests a significant contribution to any cool dust emission at 230 GHz, if the spectrum at around 100 GHz is dominated by optically-thin free-free emission. However, Seaquist et al. (1985) produced an elaborate model for both thermal and non-thermal radio emission from the core region of M 82 and also predicted the continuum flux density from these two components. The radio flux density is falling steeply from low to high frequencies and a simple extrapolation to 230 GHz indicates a contribution of less than about 0.25 Jy to the cool dust emission. More recently, Klein, et al. (1988) reported on their multi-wavelength radio observations of M 82 and presented a composite spectrum from all the infrared and radio observations of the galaxy to date (their Fig. 3). Their study shows that (1) free-free emission contributes no more than ~0.15 Jy at around 100 GHz (and less at 1.3 mm); (2) non-thermal emission contributes about 0.25 Jy at 1.3 mm; and (3) based on the far-infrared and sub-millimeter spectrum, cool dust dominates the emission at wavelengths shortward of about 1.5 mm. Indeed, our observed flux density lies squarely on the cool dust spectrum proposed by Klein et al. Based on the extensive available observations, we therefore conclude that the cool dust in emission at 1.3 mm contributes 0.9 ± 0.3 Jy. Note again that this quoted uncertainty is not the rms error, but rather is the full range of allowed values for the flux density from the dust. Thus, we have determined the flux density from cool dust at 1.3 mm to within about ±30%, which translates directly into the same uncertainty in our derived H_2 mass. This uncertainty is, we emphasize, much smaller than the range of values derived for $M(H_2)$ using a variety of techniques.

Paramount to this project was the determination of the mass of star-forming gas in the central infrared-bright core of M 82 as an alternative technique to use of the CO line emission. Among the variety of formulations to derive masses from millimeter continuum observations, we prefer

$$M(H_2) = m_{H_2}\, D^2 \left[\frac{F_\nu}{B_\nu}\right] \left[\frac{N(H_2)}{\tau}\right], \qquad (1)$$

because the equation explicitly shows the primary source of systematic uncertainty in the calculation, the value for the ratio of column density to emission optical depth of dust at the wavelength of observation, $N(H_2)/\tau$. We take this ratio to be $7\ 10^{25}$ molecules cm^{-2}, appropriate to a large variety of objects in the Milky Way (Thronson, 1988). Other terms in the equation are better known: D is distance of the object (3.3 Mpc for M 82), F_ν is the observed flux density, and B_ν is the Planck function. The *total* gas mass, including helium and the heavy elements, is modestly larger than the H_2 mass and we discuss the effects of alternative elemental abundances in the following section. From our data, we estimate $M(H_2) = 3\ 10^8\ M_\odot$ for a flux density from cool dust of 0.9 Jy and a dust temperature of $T_d = 30$ K. Thronson et al. (1987) estimated this temperature for the cool dust from the spectral energy distribution at wavelengths between 80 and 400 µm, assuming that the optically-thin dust emits as $F_\nu \propto \nu B_\nu(T_d)$. This

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spectral energy distribution is a common assumption for observations of galaxies, but readers should be wary of temperatures derived from far-infrared/sub-millimeter photometry. First, in a heterogeneous object such as a galaxy, there are a very wide range of dust temperatures appropriate to a wide range of physical conditions. As one direct consequence of this, temperatures that are derived are those to which the observing appartus is most sensitive. For example, dust temperatures derived from IRAS data at 60 μm and 100 μm always are in the range of 25–45 K, since this is the temperature of the dust that emits efficiently in that wavelength range. Second, the wavelength dependence of the dust absorption coefficient is only approximately known: observers have adopted $Q_\nu \propto \nu^{1 \rightarrow 2}$ (see the discussion in, e.g., Telesco and Harper, 1980; Hildebrand 1983; Thronson, 1988). This range of values for the exponent translates into about a ±30% variation in derived dust temperatures at wavelengths close to or a little longward of the peak of the thermal emission from the dust. In a large part because of these uncertainties, we attempted to map M 82 at the longest wavelengths for which dust emission should dominate and where, since the emission is on the Rayleigh-Jeans side, derived masses are only linearly dependent upon adopted dust temperatures and their uncertainties. If the dust temperature is uncertain by ±30%, so is our derived mass.

3. Analysis

If we did not believe that the technique that we have used produces reliable estimates of the gas mass, it would have been foolish to undertake the project as described. We are, therefore, obliged to attempt to explain the discrepancy between our results and those of other workers, particularly Jaffe et al., who used a technique to determine the gas mass that is similar to ours. These latter authors adopted a dust temperature (45 K) derived from relatively short-wavelength far-infrared data from 40 μm to 140 μm (Telesco and Harper, 1980, who derived this temperature estimate as an upper limit), while we choose to use longer-wavelength photometry (100–400 μm; from the compilation of Thronson et al., 1987) that is sensitive to cooler dust that should be more similar to the dust in emission at sub-millimeter and millimeter wavelengths (see preceding section). As a consequence, we estimate $T_d = 30$ K, resulting in a higher derived gas mass than that found by Jaffe et al. Had these authors used a lower dust temperature, the mass that they derived would have been significantly greater and in agreement with our results, since masses derived from sub-millimeter observations are sensitive to adopted temperatures. The remaining modest disagreement with the results of Jaffe et al. is a result of observational uncertainties such as calibration differences and beam size effects. We conclude that there is agreement between ourselves and Jaffe et al., if the same dust temperature is adopted.

As already noted, a major systematic uncertainty in our estimation of $M(H_2)$ is the conversion ratio, $N(H_2)/\tau$, for which we adopt a value appropriate to the solar neighborhood in the Milky Way. This ratio varies with heavy element abundance, which is different in other galaxies, and we propose a correction for the particular case of M 82. For this correction, we make the following simple argument that emphasizes the strengths of using long-wavelength continuum observations to calculate $M(H_2)$. Metal-poor (or -rich) galaxies are so because of the smaller (or larger) number of highly-evolved stars that have returned processed material to the interstellar medium. Grains, or at least their cores, are produced in the thick, extended envelopes of such stars, which should be roughly similar from galaxy to galaxy. Concerning the dust, the primary difference among galaxies with wide variations in the heavy element abundance may be simply the *number* of grains relative to the total gas mass. Size, composition, and shape of the grains may, in contrast, be very similar among the galaxies, since the mechanism of formation is similar. A possible exception is mantle size. Since $N(H_2)/\tau$ is inversely proportional to the relative number of grains, the ratio might also, therefore, be inversely proportional to the heavy element abundance relative to that of the local solar neighborhood. Quantitative determinations of the elemental abundance in M 82 are rare: the analysis of O'Connell and Mangano (1978) suggests that heavy elements are two or three times more abundant than in the solar neighborhood. Thus, a better estimate of the H_2 mass in the galaxy is $1\ 10^8\ M_\odot$, a factor of 3 lower than the value we derived by assuming a solar neighborhood metallicity. We note that, if our simple model is correct, the mass determined from 400 μm photometry by Jaffe et al. is reduced by the same factor. Similarly, the masses derived by Lo et al. from their CO observations, under the assumption of optical thinness, would probably also decrease, but this depends upon complicated cloud chemistry. In contrast, increases in heavy element abundance has a smaller effect on mass determinations under the assumption of optical thickness for the CO line, as assumed by Young and Scoville. Using our correction, the molecular mass estimated from our continuum observations falls midway among the wide range of values for $M(H_2)$ derived by CO line observers.

Although all observers of the interstellar medium in galaxies are optimistic about the accuracy of their chosen technique, when compared, variations among the results are often larger than the quoted uncertainty of the technique, as we find for M 82. A value of $M(H_2) = 1\ 10^8\ M_\odot$, derived from our 1.3 mm photometry for the inner ~40″ of the galaxy, is about a factor of two in either direction from the extremes of the CO line results. However, it is likely that masses derived from the molecular line observations will have to be significantly revised, as our mass estimates were, when accounting for the different metallicity in the galaxy.

4. Conclusion

We present and discuss 1.3 mm continuum observations of the core of the unusual galaxy M 82. We find that emission at this wavelength is not much more extended, if at all, than the size of our 33″ beam. The total 1.3 mm flux density is measured to be 1.3 ± 0.3 Jy, of which 0.9 Jy arises from cool dust in the core of the galaxy. This dust emission corresponds to an H_2 mass of about $3\ 10^8\ M_\odot$. This value might be lowered by factor of 3 when the high heavy-element abundance in M 82 is accounted for. We discuss our disagreement with sub-millimeter continuum data and argue that the earlier analysis of observations at 400 μm should be revised by use of a lower average dust temperature. The molecular gas mass that we derive is midway between the extreme values derived from the CO line observations.

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