SUBMILLIMETER CONTINUUM PROPERTIES OF COLD DUST IN THE INNER DISK AND OUTFLOWS OF M 82

LEROOTHODI L. LEEUW1,2,3 AND E. IAN ROBSON4

1 Space Science and Astrophysics Branch, NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035, USA; leroothodi.l.leeuw@nasa.gov
2 Department of Physics and Electronics, Rhodes University, P.O. Box 94, Grahamstown 6140, South Africa; leroothodi@alum.mit.edu
3 SA SKA/MeerKAT, Lonsdale Building, Lonsdale Road, Pinelands 7405, South Africa; leroothodi.leeuw@ska.ac.za
4 Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK; eir@roe.ac.uk

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ABSTRACT

Deep submillimeter (submm) continuum imaging observations of the starburst galaxy M 82 are presented at 350, 450, 750, and 850 μm wavelengths, which were undertaken with the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope in Hawaii. The presented maps include a co-addition of submm data mined from the SCUBA Data Archive. The co-added data produce the deepest submm continuum maps yet of M 82, in which low-level 850 μm continuum has been detected out to 1.5 kpc, at least 10% farther in radius than any previously published submm detections of this galaxy. The overall submm morphology and spatial spectral energy distribution of M 82 have a general north-south asymmetry consistent with Hα and X-ray winds, supporting the association of the extended continuum with outflows of dust grains from the disk into the halo. The new data raise interesting points about the origin and structure of the submm emission in the inner disk of M 82. In particular, SCUBA short wavelength evidence of submm continuum peaks that are asymmetrically distributed along the galactic disk suggests that the inner-disk emission is reradiation from dust concentrations along a bar (or perhaps a spiral) rather than edges of a dust torus, as is commonly assumed. Higher resolution submm interferometry data from the Smithsonian Submillimeter Array and later Atacama Large Millimeter Array should spatially resolve and further constrain the reported dust emission structures in M 82.

Key words: dust, extinction – galaxies: individual (M82) – galaxies: starburst – radiation mechanisms: thermal – submillimeter

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1. INTRODUCTION

Massive ejections of gas and dust originating in galactic nuclei have been observed at scales of a few kpc in optical emission lines, submillimeter (submm) molecular, mid-infrared (MIR), ultraviolet (UV), submm and radio continuum emission, and soft X-rays (e.g., Watson et al. 1984; Heckman et al. 1990; Devine & Bally 1999; Hoopes et al. 2005; Engelbracht et al. 2006). One explanation for the outflows is that a high supernova rate in the galactic nucleus heats up the surrounding gas to high temperatures with sound speeds exceeding the escape velocity of the galaxy, creating a wind that expands outward from the classical starburst galaxies (Chevalier & Clegg 1985). The wind entrains cosmic rays, warm and cool gas, as well as cool dust, making the outflow directly visible in many wavebands. The outflows are usually oriented along the minor axes of the galaxies and are thus most easily observed in edge-on galaxies. In local starbursts and high-z Lyman break galaxies with a high enough global star formation rate per unit area, the superwinds are common and responsible for expelling metals from these galaxies and enriching the intergalactic medium (IGM) and, therefore, have implications in the evolution of galaxies and the IGM (see e.g., Heckman 2003; Veilleux et al. 2005, for recent reviews).

M 82 (NGC 3034) is a nearby and popular object in which to investigate the physical association between galactic nuclei and large-scale outflows. The galaxy is edge-on with an inclination of about 10° at a position angle of 72° and is classified as IrrII. At an estimated distance of 3.63 Mpc (as determined for M 81 by Freedman et al. 1994), M 82 has optical dimensions of 11.2 × 4.3, that is, ~ 11.8 × 4.5 kpc (image scale is ~ 17.6 arcsec⁻¹). The nuclear region, within 4′ × 2′ about the major axis of the galactic disk, has numerous point sources or emission concentrations, some of which originate from supernovae and massive star clusters and have been detected from the X-ray to radio wavebands. Layers of dust filaments laden these inner regions producing severe optical extinction and copious infrared (IR) to submm reradiated emission.

New Hubble Heritage Team optical images obtained with a deep six-point mosaic in B (0.45 μm), V (0.55 μm), I (0.81 μm), and Hα (0.65 μm) filters of the Advance Camera for Surveys (ACS) on board the Hubble Space Telescope (HST) exhibit detailed, filamentary outflows of the M 82 (Mutchler et al. 2007), especially in Hα. As described above, it is thought that this outflow is being driven by the copious formation of massive stars (or a starburst) and subsequent explosions of supernovae. The starburst outflow not only provides the ejection mechanism for the material from the galactic nucleus, but also heats the gas and ionizes the hydrogen, causing it to glow with the red light of the Hα emission line.

These new optical images and earlier detailed natural-color composite images of M 82 obtained with HST (see e.g., de Grijs 2001) and the Subaru Telescope (Ohyama et al. 2002) show more than 100 compact groupings of about 10⁵ stars in very bright star clusters sprinkled throughout the galaxy’s central region, prominent dust lanes that crisscross the disk, knotty filaments of ionized gas that have rich nebular spectra that are not especially enriched in nitrogen, and hydrogen gas in a strong galactic wind that is clearly below the galactic center and to the right of the central region, along with many other regions of varying star formation environments in the nuclear parts.
of this galaxy. The huge clusters of massive stars, numerous X-ray and radio-detected supernovae, gas concentrations, optically dramatic dust filaments, galactic winds, and other active nuclear features have been attributed to a large burst of star formation $10^7$–$10^8$ years ago, which was probably triggered by a tidal interaction with the nearby spiral galaxy M 81 and dwarf starburst galaxy NGC 3077 (see e.g., Yun et al. 1994 for evidence of H II tails linking the three, and Förster Schreiber 2000 for a recent review).

The proximity of this galaxy makes it possible to observe the region of interaction between the star formation regions and the halo, including expanding shells or bubbles and “chimneys” that produce a clearer picture of the localized driving mechanisms for the outflows (e.g., Heckman et al. 1990; Wills et al. 1999; Westmoquette et al. 2007). The proximity also allows the detections of low-level emission in the halo and consequently the determination of the amounts and possible origin of material that result in this emission (e.g., Seaquist & Clark 2001; Engelbracht et al. 2006). Studying the contents and interactions between the star formation regions and the halo is important for understanding their role in the evolution of M 82 and may provide clues to general galaxy evolution as well as details of the composition of the intergalactic material.

This paper focuses on the Submillimeter Common-User Bolometer Array (SCUBA) maps of the copious submm rarediated emission that results from the dust-laden, star-forming disk, as well as large-scale, low-level emission that is associated with the outflows in the halo of M 82. Submm continuum observations of the dusty central regions in M 82 were previously obtained with the submm continuum receiver UKT 14 on the James Clerk Maxwell Telescope (JCMT) by Hughes et al. (1990, 1994) and later with SCUBA, and also on the JCMT, by Leeuw et al. (1999) and Alton et al. (1999). The current study was intended to extend these previous imaging submm observations in spatial extent and sensitivity, and to all the four submm wavelengths available with the SCUBA array (see Section 2). The study includes a coaddition of data mined from the SCUBA Data Archive.

The co-added data produce the deepest submm continuum maps yet of M 82, in which low-level emission is detected out to 1.5 kpc for the first time in the submm continuum of this galaxy. The deep maps are used in a detailed morphological study of the nuclear and large-scale detections (see Sections 3 and 5), including a focused comparative analysis with optical (see Section 3.2) and high-resolution CO (1–0) (see Section 3.1) morphology. The maps are also used in the computation the first submm spatial spectral energy distribution (SED) of separate locations in the nuclear star-forming region of M 82 (see Section 5). These observational results are used in the discussion of the origin and structure of submm continuum morphology and spatial SED of M 82 and reviewed in the context of relevant interpretations by other researchers, including those who use data from other wavelengths (see Section 5). In particular, (1) the commonly assumed interpretation that the double emission peaks that are seen in the mm-to-infrared continuum are due to emission from the edges of an inclined, dusty molecular torus is challenged (see Section 5.1), (2) an analytical review of CO results is undertaken to assess if CO emission may significantly contaminate the continuum observed in SCUBA filters (see Section 4), and (3) a morphological comparison is conducted to check whether the localized outflows that are reported in high-resolution radio, CO, and SiO maps by Wills et al. (1999), Weiß et al. (1999), and García-Burillo et al. (2001), respectively, can be seen in the SCUBA maps (see Section 5.3). Finally, the overall implication of the results is discussed and possible future work is outlined (see Section 6).

### Table 1

The CSO Relations Used on the Data Presented in This Paper

| $\tau_{CSO}$ | $\tau_{SCUBA}$ | $\tau_{SCUBA}$ - $\tau_{CSO}$ |
|------------|--------------|-----------------|
| 4.3        | 0.007        |                  |
| 23.9       | 0.01         |                  |
| 6.5        | 0.03         |                  |

2. OBSERVATIONS

SCUBA 850, 750, 450, and 350 $\mu$m imaging observations of M 82 were obtained with the telescope pointed at the 2.2 $\mu$m IR nuclear peak of the galaxy using positions from Dietz et al. (1986). Jiggle mapping observations were conducted with the secondary chopping in azimuth at 7.8 Hz and with a throw of 120$\arcsec$. The imaging observations employed the common 64 point jiggle pattern with a 3$\arcsec$ offset between each position, giving fully sampled images with both arrays.

Because M 82 has been a popularly observed source with SCUBA, additional maps that were obtained with a chop throw of 120$\arcsec$ by other observers were mined from the SCUBA Data Archive in order to co-add the related data and maximize the signal to noise in the final maps. Following JCMT guidelines by Sandell (2001), data sets from the SCUBA Archive were separately flux calibrated and corrected for JCMT pointing errors and then co-added, with each observation being weighted according to its relative integration time and the noise in the map. The 450–850 $\mu$m dual mapping wavebands have been used more commonly than the 350–750 $\mu$m combination, and therefore the archival maps constitute about 85% and 35% of the respective co-added, total-integration time for the 450–850 $\mu$m and 350–750 $\mu$m dual maps.

The imaging data analysis was undertaken using the dedicated SCUBA data reduction software SURF (Jenness et al. 1998), as well as KAPPA, GAIA, and CONVERT software packages provided by the Starlink Project. The data reduction consisted of first flat fielding the array images and then correcting for atmospheric extinction. Next, pixels significantly noisier than the mean were blanked out and, after initial inspection of raw images, pixels containing relatively little flux from the source were used to correct for correlated sky noise in each individual jiggle map.

The atmospheric opacity, $\tau$, was determined from skydips made with SCUBA at intervals during the observations. Were SCUBA skydip measurements were not available, $\tau$ at the SCUBA filters was extrapolated from the continuously measured $\tau$ at 225 GHz, obtained courtesy of the Caltech Submillimeter Observatory (CSO) radiometer and using relations listed in Table 1. At the JCMT, these relations are empirically derived and periodically updated and improved as more data, especially since the commissioning of SCUBA, have been obtained (e.g., Archibald et al. 2002). All the data were calibrated using instrumental gains primarily determined from nightly beam maps of Mars and Uranus or, alternatively, the JCMT secondary calibrators.

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5 The Starlink Project is run by the Council for the Central Laboratory of the Research Councils on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom.

6 This latest documentation is available at the Joint Astronomy Centre Web site, http://www.jach.hawaii.edu.
3. THE GENERAL SUBMM CONTINUUM MORPHOLOGY

Figure 1 shows the 850, 750, 450, and 350 μm co-added maps of M 82 that were obtained in a jiggle-mapping observing mode, respectively, at 14′.5, 11′.4, 8′.5, and 6′.7 resolutions and about 8, 100, 225, and 650 mJy/beam sensitivities. The 850 and 750 μm images have a single emission peak that is centered about 9′ west of the galactic nucleus, while the 450 and 350 μm maps have two emission peaks centered about 10′ and 6′, respectively, east and west of the nucleus along the galactic disk. The peak in the west is slightly elongated along the galactic disk and is brighter than the eastern peak, showing east-west asymmetry about the nucleus. In the 750 μm image, the single emission peak seen in the 850 μm image begins to be resolved out into the double peaks seen in the 450 and 350 μm images (e.g., Figure 1, bottom panel). This is expected, as the 750 μm observations have a resolution that is intermediate between that of 850 and 450 μm. When the maps at shorter wavelengths (e.g., 350 μm) are smoothed to resolutions similar to those at the longer wavelengths (e.g., 850 μm), the two submm peaks that are resolved at the shorter wavelengths become visible just as one peak, showing that indeed the different high-brightness morphologies depicted in the maps are due to the respective resolutions at different wavelengths. The overall extended morphology has an elliptical shape with the major axis position angle of 72°, that is, roughly the same as the galactic disk in the nuclear region. This general morphology is similar to previous continuum observations at mm (e.g., Kuno & Matsuo 1997; Thuma et al. 2000), submm (Hughes et al. 1994; Leeuw et al. 1999; Alton et al. 1999), and MIR (Telesco et al. 1991) wavelengths, as well as to CO line transition (e.g., Nakai et al. 1987; Thuma et al. 2000) observations of comparable resolution.

It is noted that although the maps presented in Figure 1 have features similar to those in published submm continuum maps by Hughes et al. (1994) and Alton et al. (1999), the very sensitive 850 μm map presented here also shows that the 850 μm emission (that is expected to be from cold dust) extends by at least 10′ (≈176 pc) radius farther into the halo than detected by those authors. Furthermore, Figure 2 depicts the 850 μm continuum emission and integrated CO (2–1) line intensity maps, respectively, presented in Figure 1 of this paper and Figure 5 of work by Thuma et al. (2000), to show that the 850 μm emission is as extended as the CO (2–1) emission, in contrast to claims by Thuma et al. (2000) that the CO (2–1) emission is more extended than the cold dust emission of M 82, and therefore made the galaxy exceptional in this regard.

3.1. Submm Versus High-Resolution CO (1–0) Morphology

Figure 3 shows black contours of the integrated intensity CO (1–0) data, which were obtained with the Berkeley Illinois Maryland Association (BIMA) interferometer by Shen & Lo
Figure 2. Deep maps of the 850 μm continuum emission (left) and integrated CO (2–1) line intensity (right) of M 82, respectively, as presented in Figure 1 of this paper and Figure 5 of work by Thuma et al. (2000). The respective beams for the two observations are plotted and the rest of the keys, contour lines, axes are as presented in the indicated figures. A scale bar of \( \sim 1.5 \) kpc is shown on the maps.

Figure 3. Central 76″ × 56″ region of M 82 at 850 (left panels) and 450 μm (right panels) overlaid with the integrated intensity (black contours) of the CO (1–0) interferometry data by Shen & Lo (1995). The top panels are plotted at full resolution of the CO contours and the bottom panels are with the CO contours smoothed to beam sizes similar to the SCUBA 850 and 450 μm beams (\( \sim 14′.5 \) and 8′.5, respectively). The white 850 and 450 μm contours on the respective maps are (200–1175) and (900–6000) mJy/beam, as displayed in Figure 1. The red 850 and 450 μm contours are at 1350 and 6800 mJy/beam and are plotted to highlight the position of the respective western submm peak. The cross marks the 2.2 μm peak (Dietz et al. 1986). The keys are color-coded intensities in Jy/beam and the X- and Y-axes are J2000 coordinates.

(1995), overlaid on the SCUBA 450 and 850 μm continuum images by aligning the sky coordinates in the SCUBA maps to those of the BIMA ones. The BIMA maps are at resolution 2′.4 × 2′.6 and are plotted to investigate the spatial correspondence between the submm continuum morphology and the high-resolution CO features. The top panels in Figure 3 are plotted at full resolution of the BIMA CO contours and the bottom panels are with the CO contours smoothed to beam sizes similar to the SCUBA 850 and 450 μm beams (\( \sim 14′.5 \) and 8′.5, respectively). Because dust often occurs mixed-in with gas in
star-forming regions, the BIMA maps are expected to give an indication of how dust emission may appear at higher resolution and perhaps also some insight into the structure seen in the SCUBA images. The BIMA maps probably provide the best observational, high-resolution evidence of structure in the inner disk that is associated with dust, as submm continuum observations of dust in M 82 are not currently publicly available at a resolution higher than 6′′.7, which is obtainable with SCUBA at 350 μm.

The first obvious difference between the SCUBA and high-resolution BIMA maps is that the dust emission peak indicated by a red contour is resolved into two peaks centered about 9″ apart in the CO maps. Of these two CO western peaks, the one closer to the nucleus is cospatial with the 450 μm (red contour) and slightly east of the 850 μm (red contour) western peaks. The CO peak farthest from the nucleus is actually the brightest of all the CO peaks and lies on the eastern edges of the submm 850 and 450 μm high brightness lobes, not coincident with the brightest submm peaks. Distinct from submm continuum, the lower-level CO emission near the very western CO peak fans out westerly at a position angle of 85°, diverting from the 72° position angle of the submm continuum lobes and disk along the major axis, as well as that of the CO within a 10″ radius from the galactic nucleus. These differences in the CO and dust features are evident in both the full resolution and smoothed CO maps plotted in Figure 3, suggesting that although the dust and CO generally appear mixed in this star-forming region, in fact there are differences in their spatial distributions. The different concentrations are most probably locations of varying gas-to-dust densities or star formation environments. Consistent with the finding here of different CO dust concentrations, evidence of a star formation history (e.g., de Grijs 2001) and gas density (e.g., Pettipas & Wilson 2000) that clearly varies from the east to west of the galaxy has been reported in M 82.

Higher resolution submm observations of dust in M 82 that should be possible with the Smithsonian Submillimeter Array (SMA) and later Atacama Large Millimeter Array (ALMA) will provide direct observational evidence to further test how different the CO and dust emission trace each other at the small scales shown in the BIMA maps. These future observations will also test if dust emission has more complex morphology than has currently been detected, as is suggested by the increasing structure that is seen in the SCUBA maps going from low to high resolutions. Further discussion of the origin and structure of the submm emission peaks is detailed in Section 5.

3.2. Submm Versus IR and Optical Morphology

The spatial investigation of submm versus IR and optical morphology in M 82 is important because complex optical morphology that is seen in this galaxy, with visual extinction values (A_ν) that range from about 3 to 25 (e.g., Alonso-Herrero et al. 2001), is thought to result from obscuration of optical light by large, cold dust grains that are heated by stars (among other things) and reradiate in the IR to submm wavelengths. Evidence of star formation history (e.g., de Grijs 2001), gas density (e.g., Petitpas & Wilson 2000), and submm and CO emission peaks (this work; e.g., Section 3.1) that clearly vary from the east to west of the galaxy strongly suggest that any associated dust lanes must vary not only in their geometric structure but also in their heating mechanisms and composition.

3.2.1. Strong Optical-Obscuration Patches that Correspond with Submm and CO Peaks

The panels in Figure 4 show the B-band maps of M 82 obtained by the Hubble Legacy Team (Mutchler et al. 2007), overlaid with the 450 μm continuum-emission contours shown in Figures 1 and CO (1–0) interferometry data by Shen & Lo (1995). For best contrast, the optical intensities are inversely plotted and therefore the light patches are extinction features. The central cross and open squares respectively mark positions of the 2.2 μm peak by Dietz et al. (1986) and MIR, star-forming clusters by Lipsy & Plavchan (2004). The X- and Y-axes are J2000 coordinates.

Figure 4. The left and right panels respectively show the B-band maps of M 82 obtained by the Hubble Legacy Team (Mutchler et al. 2007), respectively, overlaid with the 450 μm continuum-emission contours shown in Figures 1 and CO (1–0) interferometry data by Shen & Lo (1995). For best contrast, the optical intensities are inversely plotted and therefore the light patches are extinction features. The central cross and open squares respectively mark positions of the 2.2 μm peak by Dietz et al. (1986) and MIR, star-forming clusters by Lipsy & Plavchan (2004). The X- and Y-axes are J2000 coordinates.
and very dense optical obscuration patches about the nucleus. The most western and brightest CO peak also coincides with a dense optical obscuration patch.

Within a radius of about 10′ about the galactic nucleus, or about 2 arcsec north of the 2.2 μm peak (Dietz et al. 1986), there is intense B-band optical emission. This region is between the two submm peaks and thus has relatively low submm intensity or, if indeed the submm emission is from cold dust reradiation, low density or heating of cold dust. This region also has mid-IR emission indicative of star formation clusters (Lipsky & Plavchan 2004), though of less MIR brightness and lower MIR color temperature than the star formation clusters southwest of this position, that is, at the location of the southwestern submm peak. The remarkable spatial coincidence between the submm as well as high-resolution CO peaks and very dense optical obscuration patches about the nucleus, and the coincidence of intense B-band optical emission with the location of relatively low submm emission or cold dust column density, support suggestions in this paper that the submm emission in the inner disk of M 82 originates from reradiation of dust concentrations or clouds of physically different star formation environments (e.g., Achtermann & Lacy 1995; Förster Schreiber 2000; de Grijs 2001), rather than the commonly assumed interpretation of a dusty torus about the nucleus (see Section 5.1).

In color images of M 82 (see e.g., de Grijs 2001; Westmoquette et al. 2007), the optical emission associated with submm peaks and high brightness diffuse reradiation in the inner disk of this galaxy has a blue-brownish hue, strongly suggesting that hot, young, blue stars are the main heating source for the dust in this inner region. The young stars also produce IR emission and emission lines associated with intense star formation and emission lines associated with hot, young, blue stars, which are the main heating source for the dust in those regions. The relatively larger SCUBA beam could also smear and thus erase small features detected in the higher resolution optical maps.}

3.2.2. Strong Optical-Obscuration Patches with No Corresponding Submm and CO Peaks

Although all the submm and CO peaks correspond to optical features in the inner disk of M 82, as described above, the contrary is not true; that is, many prominent optical filaments, clouds, and lanes, as well as dust, have no clear corresponding submm emission counterparts. In particular, the submm emission is basically smooth at the locations of (1) north-south filaments that run below, through, and flare above the southwestern submm peak that is about 8″ from the galactic nucleus; (2) east-west dark lanes that run west along the galactic major axis and continue through to about 35″ west of the galactic nucleus (or 25″ west of the southwestern submm peak); (3) a huge, dramatic complex of optically obscuring clouds, filaments, and lanes that extends the entire minor axis of M 82′s disk and covers an area greater than a diameter of 25″ south of the disk just east of the eastern submm peak that is about 10″ from the galactic nucleus; and (4) light, optically obscuring clouds and filaments in a “low”-extinction region known as a starburst remnant (e.g., de Grijs 2001) that lies about 30″ to 60″ northeast of the galactic nucleus. In another region of low optical extinction and radiation that is about 60″ to 120″ northeast of the galactic nucleus, submm emission has currently not been detected where very light optically obscuring filaments are evident.

The lack of correspondence between the very dark optical clouds, filaments, and lanes with bright submm emission suggests that these optical features are due to obscuration by cool dust grains that are on the near side of the galaxy and at large distances from the nuclear region, where they are heated by a very dilute stellar radiation field. These foreground dust clouds evidently have enough column densities to obscure optical light in the line of sight (LOS); however, they only re-emit very low-level emission that shows no striking features in the current submm maps. That the complex optical morphology seen in Figure 4 is primarily due to foreground dust is supported by the fact that the obscuration is more dramatic in the shorter wavelength B-band than longer I-band images (L. L. Leeuw et al. 2009, in preparation). Obscuring dust is expected to be optically thicker at the shorter wavelength and, therefore, cause more optical extinction and thus appear more prominently at the shorter wavebands.

One explanation for the submm low-level continuum having a relatively smooth morphology is that, because this emission is optically thin, the detected radiation at a particular submm wavelength represents the total emission from the entire galactic column of dust in the LOS. This is different from the optical morphology of dust because the dust is typically seen obscuring stellar light, and, therefore, only the dust in certain spatial stratifications (usually the foreground) of the LOS column is observed. In other words, morphology due to spatial depth or stratification of similar dust grains that are heated by a dilute radiation field is most often more obviously seen in optical obscuration than in submm emission. These morphological effects will of course depend on the sensitivities and resolutions of the instruments used. In a low optical extinction and radiation region about 60″ to 120″ northeast of the galactic nucleus, for example, the lack of any submm detection to date may be simply due to the fact that current continuum instruments have not been sensitive enough to easily detect low-level dust reradiation that might correspond to low-level extinction and stellar heating in those regions. The relatively larger SCUBA beam could also smear and thus erase small features detected in the higher resolution optical maps.

3.2.3. The Outflowing Wind

An alternative explanation for the submm morphology of M 82 being smooth as opposed to disrupted like the optical morphology depicted in Figure 4 is that the submm low-level emission is primarily due to dust entrained in outflowing gas and physically different from the optical extinction features that do not have any currently detected submm counterparts. Figure 5 shows the low- and high-brightness features of the Hα maps obtained by the Hubble Legacy Team (Mutchler et al. 2007), overlaid with SCUBA 850 and 450 μm continuum-emission contours, as shown in Figure 1. For best contrast, the optical intensities are inversely plotted and the light patches (e.g., across the center of the image in the right panel) are foreground extinction features. The Hα emission is plotted saturated to highlight the large scale and base of the outflowing Hα wind; as such, not all the obscuration patches that crisscross optical maps of M 82 are depicted here. The overlay in the left panel demonstrates the spatial coincidence between the large-scale low brightness Hα emission and 850 μm continuum north and south of the disk, while the right panel depicts the origin of the large-scale Hα emission in the intense star formation inner disk of M 82 about the submm emission peaks (especially near the southwestern peak), where a ~ 130 pc expanding “superbubble” has been discovered in CO (Weiß et al. 1999) and ionized gas (Wills et al. 1999).

Recent large-scale high-resolution Owens Valley Radio Observatory (OVRO) observations by Walter et al. (2002) detected resolved molecular CO (1–0) streamers in and below
M 82’s disk that have kinematical signatures different to its outflowing gas. Some of the streamers are well correlated with optical obscuration features and form the basis of some prominent tidal H\textsc{i} features (Yun et al. 1993) that are thought to provide evidence that the gas within the optical disk of M 82 is disrupted by the interaction of M 82 with M 81 and likely triggers the starburst activity in M 82’s center (Walter et al. 2002). The detection of resolved MIR to submm emission that corresponds to the optical and gas streamers and is perhaps a physically separate component to the outflowing gas and dust in M 82 should be possible with sensitive and high-resolution MIR-to-submm imaging instruments using \textit{Spitzer}, ALMA, and the SMA. New \textit{Spitzer} observations reported by Engelbracht et al. (2006) did indeed detect extended MIR emission not only in the outflow of M 82 but also in its halo. The extended halo MIR emission could be from material ejected into the halo by the outflowing wind or from the interaction of M 82 with M 81 (Engelbracht et al. 2006). Future observations with these sensitive instruments and their detailed data analysis have the potential to (1) directly uncover the disruption of cold (and warm) dust distribution by the interaction of M 82 with M 81; (2) decompose submm dust emission in the disk, outflows, and streamers of M 82 and better constrain the properties of cold dust in these separate components (see Section 5.3); and (3) elucidate the role or consequence of the dust in the interaction of M 81 and M 82 (e.g., Yun et al. 1993), any connected triggering and evolution of the star-forming in M 82 (see Walter et al. 2002), and the reprocessing of galactic dust in general.

4. POSSIBLE CO CONTAMINATION OF THE SUBMM CONTINUUM?

It is worth noting that the dust morphology that is mapped in the submm continuum from M 82 may be substantially enhanced by CO emission from this galaxy. A recent flux comparison between CO (3–2) emission and 850 \(\mu\)m continuum in M 82 showed that CO makes a 47\% (i.e., high) contribution to the integrated continuum in this SCUBA band (Seaquist & Clark 2001). By analyzing collated CO (4–3) observations together with those of CO at lower transitions, Guesten et al. (1993) concluded that the line strengths in M 82 increased as one went to higher transitions, indicating that the higher transitions must provide significant cooling in the galaxy. All SCUBA bands have roughly the same widths, that is, 30 GHz, and, therefore, the CO contribution to the higher frequency continuum would be expected to be equal to or more significant than that reported for the 850 \(\mu\)m band by Seaquist & Clark (2001). However, because the submm continuum in M 82 has a thermal spectrum (e.g., Hughes et al. 1994; and Section 5.2) and, therefore, the submm fluxes increase with frequency, the CO contribution to the higher frequency continuum may be less than the estimates for the 850 \(\mu\)m band. For SED analysis in this paper (see Section 5.2), the CO percentage contribution to the measured flux is assumed to be the same across the SCUBA bands and no correction for it is made in the presented data.

Observations using a new high-frequency Fabry–Perot spectrometer on the JCMT have led to clear detections of the high transition CO (7–6) in M 82 and NGC 253 (Bradford et al. 1999), the first such detection in any extragalactic sources. The analysis by Guesten et al. (1993) and the detections of CO (7–6), whose transition line lies in the 450 \(\mu\)m filter bandpass, suggest that other higher transition lines, such as the 13CO (8–7) line that lies at the center of the SCUBA 350 \(\mu\)m band, could be very strong in M 82, supporting the above proposition that the high-frequency SCUBA images may have significant contribution from CO. In this light, the morphology seen in the SCUBA images is a direct probe of the galactic cooling and the general interactions of active star formation and the ISM in M 82.

Although it is not obvious if the CO contribution to the higher frequencies of SCUBA will be less than or as significant as estimates by Seaquist & Clark (2001), it is clear that the CO contamination to higher frequency continuum warrants investigation. Future work on this galaxy will attempt to acquire the data of the CO lines in the 450 and 350 \(\mu\)m bands and make a quantitative comparison of these data in order to determine the possible contributions of CO to the high-frequency SCUBA data. Such work is important (among other things) in the determination and interpretation of submm SED and thus the nature of dust emission in M 82 (see Section 5.2).
5. ORIGIN OF SUBMM CONTINUUM AND SED

5.1. Source and Structure of the Submm Continuum in the Inner Disk

The radiation from M 82 at the radio (e.g., Seaquist & Odegard 1991; Wills et al. 1999), mm (e.g., Hughes et al. 1990), and submm-to-IR (e.g., Telesco et al. 1991; Hughes et al. 1994; Alton et al. 1999) wavelengths is respectively dominated by synchrotron emission from supernovae, free–free emission from ionized gas, and thermal reradiation from dust heated by young stars. In this light, the double peaks seen in the mm- to-IR continuum have been commonly interpreted as due to emission from the edges of an inclined, dusty molecular torus, which—as a result of their geometry on the plane of the sky and optically thin nature of radiation—have relatively high optical depths in the LOS (e.g., Hughes et al. 1994). In Figure 1, and other mm-to-IR maps of similar or worse resolution (such as those from Infrared Astronomical Satellite (IRAS)), the double peaks are not resolved and appear as a single, elongated lobe that is brightest in the southwest. Like the galactic disk, the lobe (or peaks when resolved out) has a position angle of roughly 72° and—in the tori interpretation (e.g., Shen & Lo 1995)—an inclination of ~10°.

The peaks of emission seen in the mm to IR have alternatively been interpreted simply as dust and molecular concentrations along the galactic disk, perhaps in a bar structure (e.g., Neininger et al. 1998; Westmoquette et al. 2007) that may have an expanding “superbubble” of gas centered at supernova remnant 41.9+58 (e.g., Weiß et al. 1999; Wills et al. 1999). This interpretation is supported by at least three reasons. First, the east-west double peaks have now been seen in maps of both optically thin and thick CO emission (e.g., Petipas & Wilson 2000). This is reasonable if the emission is from a structure that constitutes concentrations or clouds of dust but is in contrast to what is expected if the emission is from a structure with tori geometry that, like the galactic disk, is thought to be highly inclined (e.g., Shen & Lo 1995). For optically thin radiation, it will be possible to detect emission from the inner parts of the imaged structure, and either dust clouds or indeed edges of an inclined torus would manifest as regions of relatively higher optical depth or brighter optically thin emission in the LOS (e.g., Hughes et al. 1994). However, as also noted by Neininger et al. (1998) and Petipas & Wilson (2000), for optically thick radiation, it will be possible to directly detect emission only from the foreground surface of the imaged structure. In that case, the dust clouds will be seen as two emission peaks, while the torus (or bar) will manifest as an elongated, bar-like emission of roughly the same optical depth or optically thick brightness.

Second, the two main peaks seen in maps of similar resolution as the 450 and 350 μm images in Figures 1 are not symmetric. In maps of better resolution and sensitivity (e.g., Shen & Lo 1995; see the CO contours in Figure 3), the peak west of the nucleus has a morphology clearly different from the eastern peak and can be resolved into two or three structures. High-resolution maps obtained with the Very Large Array (VLA) by Wills et al. (1999) showed that the western peak is associated with locations of supernova explosions of higher intensity and earlier evolutionary stage than the eastern peak and confirmed the discovery by Weiß et al. (1999) of an expanding “superbubble” that is centered near the location of M 82’s brightest supernova remnant, 41.9+58, and the submm western peak. The varying supernova intensities and ages across the disk of M 82 are supported by high-resolution HST imaging of stellar clusters that indicates that the regions near the eastern and western submm peaks have different star formation histories (e.g., de Grijs 2001). In this light, the submm peaks indicate concentrations of dust environments associated with different locations of varying supernova and star formation activities, and not the commonly assumed dust torus.

Third, observations of line ratio gradients indicate that the average temperature across the lobe increases from the northeast to southwest, while the density increases in the opposite direction (e.g., Petipas & Wilson 2000). Further evidence of the higher temperature or, at least, column density in the southwest is seen in the lopsided 850 and 750 μm lobes and the double-peak 450 and 350 μm lobes in which the southwest parts are the brighter. A torus that probably houses and is heated by an active galactic nucleus (AGN; e.g., Muxlow et al. 1994) would be expected to have a temperature that decreases from its inner to outer walls. One explanation for the higher temperature and lower density in the southwest is linked with star formation activity that both heats and depletes the interstellar medium (ISM) at this location (Wills et al. 1999), or simply western and eastern regions of two different star formation physical environments (e.g., Achtermann & Lacy 1995; Förster Schreiber 2000; de Grijs 2001; Lipsky & Plavchan 2004). Evidence in this paper in terms of clearly asymmetric submm emission seen in almost all the presented intensity maps seems to disfavor the commonly assumed interpretation of a dusty torus in M 82.

5.2. Fluxes and SED Analysis

Section 4 raised the possibility that CO emission may contaminate the continuum of M 82 observed in SCUBA filters. For one, significantly different contributions in the SCUBA bands imply different corrections to the measured fluxes and would affect the SED analysis using those fluxes. If the differences are significant, the SED computation and analysis should in theory only be determined after correcting or accounting for the CO contamination. It is currently not obvious if the contamination to the higher frequency continuum will be less than or higher than the 47% estimated to the SCUBA 850 μm band by Seaquist & Clark (2001), even though it is clear that it may also be important (see Section 4). While relevant CO data need to be acquired in the future to make a quantitative calculation of the relative contributions in the SCUBA bands, for the practical determination of the SEDs of M 82 in this paper, it is assumed that the CO contribution in the SCUBA bands is the same.

Table 2 shows the submm fluxes measured at specific locations across M 82 using SCUBA. The listed errors include calibration uncertainties. The submm-dominant emitting region in M 82 is within 30′′ × 15′′ about the nucleus and is associated with the most intense star formation in the galaxy. Assuming that the primary source of the submm emission is dust reradiation, the measured fluxes from this galaxy were fitted with the following thermal function:

\[ F_\nu = \Omega B_\nu(T) \left[ 1 - \exp \left( -\frac{\lambda_\nu}{\lambda_\nu^\beta} \right) \right], \]  

(1)

where \( \Omega \) is the solid angle for the emitting region, \( B_\nu(T) \) the Planck function at temperature \( T \), \( \lambda_\nu \) the wavelength at which the optical depth is unity (\( \lambda_\nu = 7.8 \, \mu m; Hughes et al. 1994 \)), and \( \beta \) the emissivity index of the grains. Due to the limited frequency sampling in the data, the temperature \( T \) and emissivity index \( \beta \) were the only parameters that were statistically determined in Equation (1).
winds (e.g., Watson et al. 1984; and see Section 3.2.3) and

Table 2
SCUBA Continuum Fluxes for Specific Locations in M 82

| Locations Parallel to M 82’s Disk Position Angle of 72° | Flux (Jy) @350 µm | Flux (Jy) @450 µm | Flux (Jy) @750 µm | Flux (Jy) @850 µm |
|------------------------------------------------------|-------------------|-------------------|-------------------|-------------------|
| @Peak Flux                                           | 18.6 ± 5.6        | 13.0 ± 2.6        | 1.8 ± 0.4         | 1.2 ± 0.1         |
| 30’ × 15”, about nucleus                              | 49.3 ± 13.7       | 28.8 ± 5.6        | 3.2 ± 0.5         | 2.3 ± 0.2         |
| 70’ × 40”, about nucleus                              | 63.4 ± 18.9       | 35.9 ± 7.0        | 7.7 ± 1.5         | 3.8 ± 0.4         |
| 30’ × 15”, 15” N of nucleus                           | 15.9 ± 4.8        | 7.6 ± 1.5         | 1.0 ± 0.2         | 0.6 ± 0.1         |
| 30’ × 15”, 15” S of nucleus                           | 12.8 ± 3.8        | 8.1 ± 1.6         | 0.7 ± 0.1         | 0.6 ± 0.1         |
| 30’ × 15”, 30” N of nucleus                           | 6.2 ± 1.9         | 2.8 ± 0.5         | 0.3 ± 0.1         | 0.2 ± 0.02        |
| 30’ × 15”, 30” S of nucleus                           | 3.1 ± 0.9         | 1.8 ± 0.4         | 0.2 ± 0.1         | 0.1 ± 0.1         |

Notes. The listed measured flux densities include roughly 47% possible contribution from CO as discussed in the text.

Table 3
SCUBA-Derived Dust Emission Properties for Locations in M 82

| Locations Parallel to M 82’s Disk Position Angle of 72° | T (K) | β | Ω (sr) |
|--------------------------------------------------------|-------|---|--------|
| 30” × 15”, about nucleus                                | 56 ± 14 | 2.0 ± 0.1 | 1.66e− 8 |
| 30” × 15”, 15” N of nucleus                              | 31 ± 3   | 2.2 ± 0.1 | 1.66e− 8 |
| 30” × 15”, 15” S of nucleus                              | 31 ± 15  | 2.3 ± 0.2 | 1.66e− 8 |
| 70” × 40”, about nucleus                                 | 27 ± 5   | 1.8 ± 0.1 | 9.05e− 8 |

Table 3 lists the derived dust T and β, as well as the Ω associated with the specified emitting regions in M 82. For the listed rectangular locations, Ω is determined from the longest side of the rectangle. The average derived T is ~ 31 K, with a minimum and maximum of ~ 27 K and ~ 36 K, respectively. The highest T’s are from regions of the highest surface brightnesses, presumably corresponding to regions of intense star formation, while the coldest T’s are at regions farthest from the nucleus. The β values range from 1.8 to 2.3 and are highest at regions farthest from the galactic nucleus. The higher β values are associated with larger and colder dust grains; therefore, the spatial SED analysis here points to colder grains more prevalent with an increasing distance from the galactic center of M 82, particularly along the minor axis of the galactic disk (see Section 5.3).

If the CO contamination in the SCUBA bands were not constant for M 82, as assumed in this paper, an SED with SCUBA fluxes may have looked different than the result above and possibly required a different interpretation. For example, a CO contamination that increased with frequency, as suggested from an analysis of lower transition CO and CO (4–3) data of M 82 by Guesten et al. (1993; see Section 4), would mean that SCUBA fluxes uncorrected for CO contamination lead to the SED indicating lower dust temperatures and/or higher emissivity indices than was actually the case. A proper correction for any CO contamination is, therefore, needed before a more definitive SCUBA SED analysis can be conducted for M 82 and is worth attempting in the future, when CO data in all the SCUBA wavebands (especially the 350 and 450 µm ones) are available.

5.3. Implications of the SCUBA data and SEDs on the Outflow of Cold Dust

In has been noted that the continuum morphology in the inner halo of M 82 has a general north–south asymmetry, which is consistent with the north–south asymmetric X-ray and Hα winds (e.g., Watson et al. 1984; and see Section 3.2.3) and the associated UV, optical, molecular, and indeed IR-to-mm structures that have been reported in M 82 (e.g., Seaquist & Clark 2001). Therefore, a simple interpretation of the asymmetric morphology of the submm continuum in the halo of M 82 is that it is a manifestation of an outflow of dust from the inner disk to the halo.

Seaquist & Odegard (1991) presented some of the earlier extensive evidence of the disk-to-halo outflows from spectral index distribution computations using radio continuum maps at several wavelengths between 0.33 and 4.9 GHz (90 and 6 cm). They found spectral indices between −0.3 and −0.6 in the inner-disk region, steepening to about −1.0 at a radius of about 1 kpc along the minor axis, and concluded that these were from relativistic synchrotron-emitting electrons that were being scattered against IR photons emitted in the inner-disk region of M 82. Recently, Wills et al. (1999) used high-resolution VLA continuum data between 1.4 and 5 GHz and computed spectral indices from −0.6 to −0.8 about 20’ north of the disk, in localized nuclear sites of the outflows that they call “chimneys.” These values are consistent with the results by Seaquist & Odegard (1991) in the same wavebands, and Wills et al. (1999) also interpreted them as indicating synchrotron emission from relativistic electrons entrained in the wind.

A thermal component in the filaments has previously been suggested based on “tentacles” observed in Ne ii maps of M 82 (Achtermann & Lacy 1995), which presumably are also a manifestation of the outflow phenomenon. In comparative SED analysis of 30” × 15” regions centered in galactic nucleus and two others 15” north and south of it, the regions north and south had respectively cooler temperatures and higher emissivity indices than the central region. This spatial SED analysis is consistent with the submm emission coming from a thermal source with a temperature decrease and emissivity index increase along the minor axes of the disk of M 82. The change of the dust properties along the minor axes has a direction similar to the radio spectral index gradient shown by Seaquist & Odegard (1991) and Wills et al. (1999), and is consistent with the north–south asymmetric Hα winds (e.g., Shopbell & Bland-Hawthorn 1998) of M 82 that has been shown to be cospatial with the submm morphology (see Figure 5 and Section 3.2.3). In this light, the submm continuum maps (and SED changes along the minor axes) indicate an outflow of dust grains that are ejected from the inner disk by, or entrained in, the starburst winds.

One explanation for the outflow being asymmetric was given by Shopbell & Bland-Hawthorn (1998), who suggested that if the star-forming disk is slightly shifted up from the galactic disk, then this would imply that there is less covering material in the north and would make collimation difficult, resulting in an immediate blow-out of material in the north. Detectors confirming that collimation is better to the south of M 82 have been made of large-scale emission extending to 1.5 kpc, and
more extended in the south, not only in optical line maps (e.g., Devine & Bally 1999), but also in CO (2–1) and CO (3–2), respectively, by Thuma et al. (2000) and Seaquist & Clark (2001). Another valuable result of the co-addition of SCUBA archive data in this paper is that the most sensitive submm maps that are displayed in Figure 1 show submm extended emission that is associated with the outflows on scales that for the first time match the 1.5 kpc CO detections noted above.

Recently reported radio “chimneys” (e.g., Wills et al. 1999), which are about 20′′ north of the disk and hypothesized to signify local blow-outs of material by supernova-driven winds, are not obvious in the SCUBA maps. However, prominent SiO features associated with the localized radio outflows have now been detected in mm heterodyne observations obtained with the Institut de Radio Astronomie Millimetrique interferometer (e.g., García-Burillo et al. 2001). These authors explain the SiO detections in a framework of shocked chemistry at the sites of the gas ejections from the starburst disk. For the moment, it appears that the shocked gas has proved to be a better probe of the localized outflows than the direct observations of dust emission in the mm-to-submm continuum.

Localized sites of the outflows or “emission spurs,” although long sought after and sometimes reported in mm-to-submm continuum and CO maps (e.g., Hughes et al. 1994; Shen & Lo 1995; Leeuw et al. 1999; Alton et al. 1999), have not been reliably reproduced in the different mm-to-submm observations. All the continuum maps in this paper also have some low-level “spurs,” but almost none are reproduced at exactly the same locations and extend to the same degrees between any two different observations. This would suggest that the spurs might be artifacts in the maps. However, if the mm and submm spurs are emission from dust outflows (and filaments, clouds, or lanes) that are of different optical depths or compositions and reradiate low-level emission in relatively narrow wavebands, the submm spurs may not be reproduced in maps at certain wavelengths and sensitivities.

It was noted in Section 3.2 that dust in M 82 is most probably within components of physically varying locations and origin or simply at different spatial depths or stratifications. The recent high resolution interferometry observations of M 82’s molecular gas by Walter et al. (2002) discovered CO (1–0) “streamers” and decoupled previously observed CO outflows (e.g., Nakai et al. 1987; Seaquist & Clark 2001) from the streamers (e.g., Yun et al. 1993), clarifying the spatial distribution and origin of the molecular gas in this galaxy. Similar, future observations with recently commissioned sensitive and high-resolution submm imaging instruments such as Spitzer and the SMA should provide tighter constraints on the spatial and optical depth properties of dust, test the reality of the reported submm spurs, and possibly detect dust reradiation streamers, clarifying the implications or associations of all these features to dust outflows and recycling in M 82 (see Section 3.2).

6. SUMMARY OF RESULTS AND FUTURE WORK ON M 82

SCUBA 350, 450, 750, and 850 μm imaging observations have been presented of the dust-laden, star-forming inner disk and large-scale, low-level emission that is associated with the outflows in the halo of M 82. The displayed maps include co-added data that were mined from the SCUBA Data Archive, resulting in the deepest submm continuum maps of M 82. The 850 μm morphology has a single emission peak that is centered about 9′ west of the galactic nucleus, while the 450 and 350 μm maps have two emission peaks centered about 10′ and 6′, respectively, east and west of the nucleus along the galactic disk, similar to previous continuum observations at mm, submm, and MIR wavelengths, as well as to CO line transitions and Hα observations of comparable resolution (see Section 3). In the 750 μm image, the single emission peak seen in the 850 μm image (see Figure 1) is predictably beginning to be resolved out into the double peaks seen in the 450 and 350 μm images. Low-level emission is detected out to 1.5 kpc for the first time in the 850 μm continuum of this galaxy, that is, at least ∼ 160 pc radius farther out than other recent studies.

The deep maps were used in a detailed morphological study of the disk and large-scale detections, including a comparative analysis of submm with optical morphology (see Section 3.2). The overall, extended submm morphology of M 82 generally resembles the optical picture in that the disk emission has an apparently elliptical shape whose major axis is clearly aligned with that of the galactic disk at a position angle of ∼ 72′. However, the submm morphology is much smoother than the optical picture, and some prominent dust cloud and filamentary lanes that are seen in the optical are not obvious in the submm continuum. One simple explanation for the submm versus optical correspondence (or lack of it) is the different resolutions and sensitivities of the presented observations. If the optical features emit submm emission, it is possible the emission is at a level lower than the current mapped SCUBA sensitivities or smeared and thus erased by the relatively larger SCUBA beam. This can be verified by future higher resolution and more sensitive submm observations that should become possible with the ALMA.

A comparative analysis of submm to high-resolution CO (1–0) morphology was further conducted (see Section 3.1). Some resolved peaks in the CO maps could be associated with unresolved features in the submm maps. However, there are differences that show that the CO and dust emissions do not trace each other in a very simple way and suggest that although the dust and CO generally appear mixed in the central star-forming region, in fact there are differences in their spatial distributions. The different concentrations are most probably locations of varying gas-to-dust densities or star formation environments, which have been reported in M 82 (e.g., de Grijs 2001; Petitpas & Wilson 2000). This can be verified by future higher-resolution observations of dust in M 82 that should be possible with the SMA and later the ALMA.

The SCUBA maps were also used in a computation of the first submm spatial SED analysis of locations within and outside the central star-forming region of M 82 (see Section 5.2) and in the discussion of the origin and structure of submm maps (see Section 5). In particular, (1) the commonly assumed interpretation that the double emission peaks that were seen in the mm-to-IR continuum are due to emission from the edges of an inclined dusty molecular torus was challenged (see Section 5.1), (2) an analytical review of CO results was undertaken to assess if CO emission might significantly contaminate the continuum observed in SCUBA filters (see Section 4), and (3) a morphological comparison was conducted to check whether the localized outflows that were reported in radio and SiO maps, respectively, by Wills et al. (1999) and García-Burillo et al. (2001) could be seen in the SCUBA maps (see Section 5.3).

Evidence in this paper in terms of clearly asymmetric inner-disk submm emission seen in the presented intensity seems
to disfavor the commonly assumed interpretation of a dusty torus in M 82. Arguments were presented to explain the inner-disk submm maps of M 82 in the context of emission from a rather complex distribution of dust concentrations that are in regions of different star formation environments, as has been reported from various studies using data at other wavelengths (e.g., Achtermann & Lacy 1995; Förster Schreiber 2000; de Grijs 2001).

It is not obvious if the CO contribution to the higher frequencies of SCUBA will be less than or higher than the 47% estimated to the SCUBA-850 μm band by Seaquist & Clark (2001). However, it is clear that the CO contamination of the higher frequency continuum may also be significant and warrants detailed investigation. Future work on this galaxy will attempt to acquire the data of the CO lines in the 450 and 350 μm bands and make a quantitative comparison of these data in order to determine the possible contributions of CO to the high-frequency SCUBA data.

The overall submm low-level morphology has a general north-south asymmetry that is similar to the Hα winds and CO and X-ray outflows that have been detected in M 82 (e.g., Shopbell & Bland-Hawthorn 1998). The submm spatial SED analysis also shows thermal properties that change along the minor axis of the galaxy disk, similar to the radio spectral index gradient by Seaquist & Odegard (1991) and Wills et al. (1999) and consistent with the north-south asymmetric, large-scale X-ray and Hα winds. Therefore, the current results support the simple interpretation (e.g., Leeuw et al. 1999; Alton et al. 1999) that the asymmetric morphology in the submm maps is a manifestation of corresponding outflows of dust grains from the galactic disk into the halo. As noted above, this work has presented low-level 850 μm continuum emission out to 1.5 kpc for the first time in this galaxy, that is, at least ~ 160 pc radius farther out than other recent studies.

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