A DEEP SUBMILLIMETER SURVEY OF THE GALACTIC CENTER

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Received 2000 August 7; accepted 2000 October 2; published 2000 December 15

ABSTRACT

We present first results from a submillimeter continuum survey of the Galactic center “central molecular zone” (CMZ), made with the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope. SCUBA’s scan-map mode has allowed us to make extremely wide field maps of thermal dust emission with unprecedented speed and sensitivity. We also discuss some issues related to the elimination of artifacts in scan-map data. Our simultaneous 850/450 μm maps have a total size of approximately 2.8’ × 0.5’ (400 × 75 pc) elongated along the Galactic plane. They cover the Sagittarius A region, including Sgr A*, the circumnuclear disk, and the 20 and 50 km s⁻¹ clouds; the area around the Pistol: Sgr B2, the brightest feature on the maps; and at their Galactic western and eastern edges the Sgr C and Sgr D regions. There are many striking features such as filaments and shell-like structures as well as point sources such as Sgr A* itself. The total mass in the CMZ is greater than that revealed in previous optically thin molecular line maps by a factor of ~3, and new details are revealed on scales down to 0.33 pc across this 400 pc–wide region.

Subject headings: dust, extinction — Galaxy: center — ISM: clouds — ISM: structure — submillimeter techniques: image processing

1. INTRODUCTION

The Galactic center provides our best opportunity to study the astrophysical processes in a galactic nucleus with high spatial resolution. These include star formation and the molecular cloud structures in a region subjected to strong shear forces, magnetic fields, and gravitational potentials. Thermal dust continuum emission traces the temperature-weighted column density of material in a less biased way than molecular line maps, which are affected by excitation, optical depth, and abundance variations. Thus, we can use the continuum emission to map the mass distribution in molecular clouds with good accuracy and sensitivity.

We used the Submillimeter Common-User Bolometer Array (SCUBA; Holland et al. 1999) on the 15 m James Clerk Maxwell Telescope (JCMT), between April 1998 and April 2000, to map the Galactic center region in the submillimeter continuum at 450 and 850 μm. The new images cover a region 4 times larger and ~100 times deeper than earlier surveys (Lis & Carlstrom 1994). The map size is approximately 2.8’ × 0.5’, or 400 × 75 pc at an assumed distance of 8.5 kpc. The map covers the entire central molecular zone (CMZ), which extends to radii of 200 pc and contains up to 10% of the Galaxy’s molecular interstellar medium (Morris & Serabyn 1996).

2. OBSERVATIONS AND DATA REDUCTION

SCUBA (Holland et al. 1999) is a submillimeter continuum bolometer camera with two arrays, one of 91 pixels optimized for 450 μm and one of 37 pixels optimized for 850 μm. In use, both arrays observe simultaneously. The resolution is 8” FWHM at 450 μm and 15” at 850 μm.

SCUBA was used in scan-map mode, in which the array is scanned across the sky at a rate of 24” s⁻¹ while chopping the secondary mirror at 7.8 Hz. This chopping produces images in which the sky is convolved with the primary beam of the telescope and a dual-beam function of positive and negative delta functions separated by the chop throw.

The majority of the map was observed six separate times, with chop throws of 20”, 30”, and 65” in both right ascension and declination, although some fields at the Galactic eastern and western ends were observed with 30”, 44”, and 68” chops. Each dual-beam image contains no information at spatial frequencies equal to the inverse chop throw and its harmonics, and the constant power level (zero spatial frequency) is also lost.

The data were reduced with SURF, the standard SCUBA reduction software (Jenness & Lightfoot 1999), using the “Emerson 2” deconvolution algorithm. This algorithm combines the multiple chop throw images of the map fields. A weighted average of these observations is formed in Fourier space, and the reverse transform yields the final map (Jenness & Lightfoot 1998). Although the combination of multiple chops improves the spatial frequency coverage, it is unavoidable that spatial scales more extended than a few times the maximum chop throw are measured with reduced sensitivity, and the zero spatial frequency is still lost. Ultimately, the survey is sensitive
Fig. 1—SCUBA Galactic center survey: 450 µm flux density

Fig. 2—SCUBA Galactic center survey: 850 µm flux density
to spatial scales in the approximate range from 0.3 pc (the beam size at 450 μm) to ~10 pc (a few times the maximum chop throw).

Calibration was performed from maps of Uranus and Mars, and all data were corrected for atmospheric extinction using sky dips. Zenith opacities were in the range 0.1–0.45 at 850 μm and 0.33–2.5 at 450 μm. Most of the data in the central 15' region were taken in extremely good weather, with τ(850 μm) < 0.13, τ(450 μm) < 0.5.

To calibrate fluxes of extended structures, the integrated signal in a 1' diameter aperture was used to calculate a conversion factor in units of janskys per squared arcsecond per volt. Calibration relative to the primary calibrators is estimated to be accurate to 5% at 850 μm and 20% at 450 μm, based on the dispersion of measured flux conversion factors, although absolute cloud fluxes also depend on corrections for constant map offsets as described in § 2.1.

The survey has resolutions of approximately 8" at 450 μm and 15" at 850 μm, corresponding to distances of 0.33 and 0.62 pc at a distance of 8.5 kpc. The 1 σ sensitivities per beam are approximately 30 and 300 mJy at 850 and 450 μm, respectively, or ~20 M⊙ beam⁻¹ with the assumptions in § 3.5.

2.1. Corrections for Artifacts

Making large-scale SCUBA scan-maps is difficult for several reasons. The total power level is not recorded, so there may be a constant offset on each field, and this offset may in general vary between fields in the mosaic. Within individual fields, one must account for baseline removal on the time series signals from the bolometers. The dual-beam chop will suppress information at certain spatial frequencies, as described above, and as there is so much extended structure in the CMZ it is difficult to scan or chop onto regions of no emission.

Some previous SCUBA scan-maps have sometimes exhibited reduction artifacts, such as negative troughs around bright sources. We have found that negative troughs can be greatly reduced by careful baseline removal on a per bolometer basis. A single 10' × 10' map is constructed from typically 10–15 scans of the array across the field. Calculating a baseline separately for each scan will produce large spurious offsets for those scans that pass over bright structure, so ideally it is best to determine a baseline using only those scans that contain little bright emission. This proved impossible for a region as rich in structure as the Galactic center, but we have found that using the median level over all the scans for each bolometer does produce good results without the spurious offsets.

This is the largest area ever scan-mapped at 450 and 850 μm, with more than 50 overlapping 10' × 10' fields, which must be mosaicked to form the final image. The Starlink CCDPACK package (Draper, Taylor, & Allan 2000) was used to combine the dual-beam images and remove relative level offsets between fields of order 10 and 0.5 mJy arcsec⁻² at 450 and 850 μm, respectively. We then applied further corrections to ensure that the pixel mean calculated along the chop throw direction was zero for all of the mosaicked dual-beam maps. This must be true, as long as the edges of the map are essentially emission-free, and is necessary because incorrect zero levels in the mosaicked dual-beam maps will translate to slopes in the final images. We finally corrected for the constant zero offset on the entire map by measuring the typical zero levels from map areas devoid of identifiable clouds and assigning an uncertainty based on the level variations. The final uncertainty in baseline levels is 15 and 1 mJy arcsec⁻² at 450 and 850 μm, respectively.

The sensitivity noise levels of the maps.

3. ANALYSIS

3.1. General Features

Our maps (Figs. 1 and 2) show good correspondence with previous surveys of the region, such as that by Lis & Carlstrom (1994) but with much higher sensitivity and resolution. At 850 μm we can clearly see the central source Sgr A* and its circumnuclear disk (l = −0.05, b = −0.05), although these features are less pronounced at 450 μm. We also see the compact giant molecular clouds (GMCs) M 0.13 0.08 (the 20 km s⁻¹ cloud) and M 0.02 0.07 (the 50 km s⁻¹ cloud). Close to this is the high-velocity molecular cloud CO 0.02−0.02 (Oka et al. 1999). At higher Galactic longitude we see the Pistol region (l = 0.15, b = −0.05), other GMCs such as M0.25+0.01 (Lis et al. 1994), Sgr B1 (l = 0.5) and B2 (l = 0.66), and the Sgr D (l = 1.1) star-forming region. At more negative longitudes, the map extends to the Sgr C (l = −0.5) star-forming region. All of the field is rich in extended structure, dominated by filamentary clouds and cavities that may be associated with supernova remnants. Such structures have also been observed by Oka et al. (1998) in CO (J = 1–0) emission.

3.2. Sagittarius A*

At both wavelengths we have a clear detection of the Sgr A* point source. By taking slices through the position of Sgr A* to determine and remove the local background, we estimate the flux from Sgr A* itself, with quoted 1 σ uncertainties. The results are also subject to the overall calibration uncertainties described in § 2. At 850 μm we measure a flux of 2.6 ± 0.3 Jy. This is consistent with the value measured with the Caltech Submillimeter Observatory and JCMT (Serabyn et al. 1997) of 3.2 ± 0.7 Jy. At 450 μm, the same procedure gives a flux for Sgr A* of 1.2 ± 0.4 Jy. This is consistent with the upper limit of 1.5 Jy found by Dent et al. (1993). These fluxes are somewhat lower than those measured by Zytko et al. (1995), which were 3.5 ± 0.5 Jy at 800 μm (rather than 850 μm) and 3.0 ± 1.0 Jy at 450 μm, suggesting that there may be some variability of the Sgr A* point source. For example, Tsuboi, Miyazaki, & Tsutsuji (1999) observed a flare at 3 mm during which the flux doubled, and Serabyn et al. (1997) found a flux of 7 ± 2 Jy at 350 μm. Our fluxes indicate a spectral index for the emission from Sgr A* of −1.5±1.0 consistent with a nondust component in the emission. Flux values for the synchrotron component from the postulated black hole are discussed further by Aitken et al. (2000).

3.3. Graybody Fitting

Although we can calculate spectral indices in the submillimeter regime from the SCUBA data, these data do not constrain the overall form of the dust emission and do not allow us to estimate the temperature of the dust. To do this, we need data around the peak of the emission, which for dust at these temperatures is in the far-infrared.

We have combined our submillimeter data with 100 μm data from the IRAS Galaxy Atlas (Cao et al. 1997) and fitted a single-temperature graybody spectrum of the form \( I_\nu = \frac{1}{(\nu\nu_0)\beta} B_\nu(T) \), where the optical depth \( \tau \) is expressed in terms of an index \( \beta \) and a critical frequency \( \nu_0 \). Although the \( \beta \) being higher in part because of the greater calibration uncertainties. These uncertainties have been neglected, compared to the sensitivity noise levels of the maps.
axy Atlas also contains 60 μm data, we believe that emission at this wavelength traces a higher temperature component. By fitting to the 850, 450, and 100 μm points, we calculate properties of the cold dust only.

We have performed a least-squares graybody fit to the three data sets over the survey area, fitting for temperature $T$ and critical frequency $f_{\text{crit}}$. We fixed $\beta = 2$, the theoretical maximum for crystalline dust grains. Since the resolution of the IRAS images was approximately 2′, the SCUBA data were also smoothed to this resolution.

The fits indicate a fairly uniform dust temperature of $\sim 21 \pm 2$ K. There are no signs of strong temperature variations correlated with individual clouds, and this is further evidence that the brightness structure in the maps is dominated by column density variations. Therefore, we adopt a typical temperature of 20 K throughout the rest of this Letter.

If $\beta$ is allowed to vary, the fit is better but the derived temperature does not significantly change. Best-fit values of $\beta$ are $\beta \sim 2.4$, higher than the canonical value of $\beta = 2$. There is now much evidence for $\beta > 2$; Lis & Menten (1998) and Dowell et al. (1999) measured $\beta \sim 2.8$ and $\beta \sim 2.5$, respectively, in GMC 0.25+0.01. In other regions, Lis et al. (1998) measure $\beta$-values as high as 2.5 in the Orion ridge, and Bernard et al. (1999) also report PRONAOS observations of high $\beta$ in the Polaris cirrus cloud. In laboratory work, Koike et al. (1995) report $\beta$ up to 2.7 in carbon-based compounds at room temperature, and Agladze et al. (1996) have shown $\beta > 2$ in silicates between $\approx 5$ and 20 K.

3.4. Spectral Index Map

We have used our 450 and 850 μm maps to generate a map of spectral index $\alpha$ (defined by $S \propto \nu^{\alpha}$), which is shown in Figure 3. We first smoothed the 450 μm map to the lower resolution of the 850 μm observations and imposed a lower threshold on both maps of $\sim 3 \sigma$, since spectral indices derived from small flux values are subject to large errors.

Over most of the bright parts of the map, $\alpha$ is in the range 3–4, indicating rather constant dust properties with a dust opacity index $\beta \sim 2$. The bulk spectral index for M0.02+0.01 (the 50 km s$^{-1}$ cloud) is $\alpha = 3.5 \pm 0.05$, whereas for M0.13+0.08 (the 20 km s$^{-1}$ cloud) it is $\alpha = 3.7 \pm 0.05$ (quoted errors are from the variation within the clouds). Assuming graybody emission at a dust temperature of 20 K, these indicate dust opacity indices of $\beta \sim 2.2$–2.4. Although $\beta = 2$ is the theoretical upper limit for crystalline dust grains, in § 3.3 we discuss some evidence for higher values of $\beta$.

Differences in spectral index may be due to differences in temperature. Since at these temperatures, emission at 450 and 850 μm is not truly in the Rayleigh-Jeans part of the spectrum, the difference between the spectral index $\alpha$ and the dust opacity index $\beta$ is temperature dependent. It is therefore possible that two clouds may have the same $\beta$ but different temperatures, leading to different spectral indices. If this were the case, a lower $\alpha$ would indicate a cooler cloud. This cannot account for all the $\alpha$ variations; for example, $\alpha$ is low at only 3.2 ± 0.1 for CO 0.02–0.02, and this cloud is thought to be relatively hot at $\sim 60$ K (Oka et al. 1999). In § 3.3, we detect no significant temperature variations on $\sim 2′$ scales.

3.5. Cloud Masses

To estimate the total cloud masses from their integrated fluxes, we require the grain absorption cross section per unit mass of gas and dust. We have adopted the parameters suggested by Pollack et al. (1994) with opacity index $\beta = 2$ and a correction for Galactic center metallicity $Z/Z_\odot = 2$ (Mezger et al. 1989). We thus derive opacities of $\kappa_{450 \mu m} = 4.94 \times 10^{-3}$ m$^{-2}$ kg$^{-1}$ and $\kappa_{850 \mu m} = 1.38 \times 10^{-1}$ m$^{-2}$ kg$^{-1}$. Assuming a uniform dust temperature of 20 K, we have for $\lambda = 450$ and 850 μm conversion factors of 63.3 and $513 M_\odot$ Jy$^{-1}$, respectively. The total mass found by the survey, measured by integrating the total 850 μm brightness, is then $(53 \pm 10) \times 10^5 M_\odot$.

The largest source of error in these mass measurements is our uncertainty of the dust temperature. The value of 20 K is derived in § 3.3, but Lis, Carlstrom, & Keene (1991) adopt a mean temperature of 30 K. However, the Infrared Space Observatory study of GMC 0.25+0.01 by Lis & Menten (1998) gives a mean temperature of $\sim 18$ K for this core, suggesting that the lower dust temperatures are correct. We neglect optical depth effects as the emission is optically thin at 850 μm except from Sgr B2.

4. FURTHER DISCUSSION

The improved depth, resolution, and extent of the SCUBA survey reveal many new features in the Galactic center. Not only
are there the known large star-forming cloud complexes, but also a wide-ranging network of dusty filaments is revealed. For example, at negative Galactic longitudes close to \( b = 0 \) there is filamentary structure that may be continuous and stretches along the Galactic plane for up to 0\(^\circ\)8 (120 pc). There are partial shells, possibly associated with the known supernova remnants Sgr A East (G0.0+0.0), G0.3+0.0, G0.9+0.1, and G1.4−0.1 (Green 1998). There is also a circular shell of dust clouds centered on \( l, b = (0.8, −0.18) \), which does not appear to be documented, and which we have labeled PPR G0.80\(^\circ\)20.18. This may trace a wind-blown region or perhaps a supernova remnant. In a future paper, we will contrast these structures with star-forming regions near the solar circle, comparing masses, densities, dust grain properties, and star-forming efficiency.

The total mass detected by our survey is \((53 ± 10) \times 10^5 \, M_\odot\) in the inner 400 pc. Dahmen et al. (1998) derived a weighted best estimate of the total mass in the inner 600 pc of the Galactic center using a combination of dust emission, gamma rays, and \(^{18}\text{O}\) molecular line emission. This estimate was \((20−50) \times 10^6 \, M_\odot\). The best optically thin tracer in this set is the \(^{18}\text{O}\) survey, from which was derived a mass of \(17 \times 10^5 \, M_\odot\) in the central 600 pc. Although our survey covers a smaller area, the total mass detected is significantly greater. Therefore, the SCUBA data comprise the first optically thin map to trace essentially all the mass in the CMZ at high resolution.

We are grateful to the UK Panel for Allocation of Telescope Time for the award of observing time for this project. J. S. R. acknowledges a Royal Society Fellowship, and D. P.-P. a PPARC Research Studentship. The JCMT is operated by the Joint Astronomy Centre on behalf of PPARC of the UK, the Netherlands OSR, and NRC Canada. We acknowledge the support provided by the Starlink Project, which is run by CCLRC on behalf of PPARC. We also would like to thank an anonymous referee for some very useful comments.

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