SHARC 350 $\mu$m Mapping of the Galactic Center from the Caltech Submillimeter Observatory

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Abstract.
Using the 20-pixel camera SHARC, we have surveyed the 350 $\mu$m emission from a 60' by 12' region in the Galactic center. A comparable region has been observed at 800 $\mu$m by Lis & Carlstrom (1994); the SHARC map has better spatial resolution and sensitivity to extended emission, however. This paper introduces several features not visible in prior maps of dust emission. We have detected a 10+ pc band of emission peaking at $l = -0.14^\circ, b = +0.02^\circ$, which is probably associated with the 'negative velocity arc' observed in $^{13}$CO (Bally et al. 1988). We suggest an association of a rounded 350 $\mu$m feature near the Radio Arc with an expanding shell observed in CS (Tsuboi, Ukita, & Handa 1997). Faint emission at the same Galactic longitude as the Dust Ridge (Lis & Carlstrom 1994) but at opposite latitude is visible as well as a compact source at the base of a thermal radio filament at negative Galactic latitude. Diffuse dust emission within a few arc-minutes of the Sgr D core is detected for the first time. 350 $\mu$m sources are associated with both H$_2$O masers in Sgr D, but only one out of four OH masers (Mehringer et al. 1998). The mean 350 $\mu$m/800 $\mu$m flux ratio for the Galactic center is approximately 17 ($\beta \sim 2.0$) over the map but is higher ($\beta \sim 2.5$) in parts of the Dust Ridge and lower in Sgr B2 (N).

1. Introduction

Submillimeter continuum observations of the Galactic center provide a measure of the amount and structure of dense material on scales of 0.5 - 200 pc. Broadband observations at 350 $\mu$m suffer very little from contamination by molecular line, free-free, and synchrotron emission, and, except toward the Sgr B2 core, the emission is optically thin.

Lis & Carlstrom (1994) mapped a large portion of the Galactic center at 800 $\mu$m using a single bolometer and an 'on-the-fly' mapping technique; many sources were detected for the first time, including cold clouds not seen in the far-IR ($\lambda < 100$ $\mu$m). However, the beam size of the experiment ($30''$) was larger than can be obtained at shorter wavelengths, and the observing time per unit solid angle was small. These shortcomings have been addressed by mapping the region at 350 $\mu$m with SHARC, a multi-pixel bolometer camera.
Figure 1. 350 μm map of the Galactic center. The beam size is 15″. The intensity scale wraps around and becomes nonlinear above 145 Jy/beam. For position reference, Sgr A* is located inside the Circum-Nuclear Disk ('CND'), and the non-thermal radio filaments (not shown) cross the Galactic plane near the Sickle (G0.18–0.04).
2. SHARC Observations

SHARC (Wang et al. 1996) uses a linear array of 20 bolometers. Each pixel subtends 5" by 10". The diffraction beam and choice of smoothing algorithm lead to an effective resolution of 15" FWHM in our map.

The data were acquired by 'on-the-fly' mapping (chopping and continuous scanning) and restored with the NOD2 algorithm (Haslam 1974). The observations took place during April-September 1998. During the very dry conditions in April, the point-source sensitivity per pixel was ~2 Jy s^{0.5} at Galactic center transit. However, due to map reconstruction noise and correlated sky noise (causing striping), the sensitivity in the raw resultant map is degraded. Fourier filtering was applied to the map to remove the sky noise stripes on rapid time scales (spatial wavelengths \leq 30") ; the filtering was quite satisfactory in that source structure was preserved. After filtering, the typical small-scale noise was 6 Jy RMS over most of the map.

The SHARC map is shown in Figure 1. The coverage is approximately 0.3 square degrees. Some imperfections are evident in the map. There are reconstruction artifacts to the east and west of the bright peaks of Sgr B2, a few regions of negative flux caused by emission at the ends of the scans, and signal-to-noise variations.

There is very good correspondence between the features in our 350 \mu m map, the 800 \mu m map of Lis & Carlstrom (1994), and the 1.3 mm map of Mezger, Duschl, & Zylka (1996) where coverage and sensitivity permit comparison. In general, we confirm the poor association of 350 \mu m dust emission with mid- and far-infrared (\lambda < 100 \mu m) and radio continuum emission. The 350 \mu m map resembles maps of some molecular transitions, however (NH_3 – Güsten, Walmesley, & Pauls 1981; CS – Serabyn & Güsten 1987).

Calibration was accomplished by observing Uranus, assuming a temperature of 64 K (Griffin & Orton 1993). The map calibration assumes point-like sources, and map fluxes are given as Jy/15" beam. The calibration uncertainty is 25%.

3. Discussion

3.1. Source Fluxes

The source fluxes measured in our 350 \mu m map are given in Table 1. Assuming a dust temperature of 30 K (Lis & Carlstrom 1994), a grain emissivity of Q(350 \mu m) = 1.9 \times 10^{-4}, a grain density of 3 g/cm^3, a grain radius of 0.1 \mu m, a dust-to-gas density ratio of 0.01, and a distance of 8.5 kpc, the conversion from flux to gas mass is approximately 20 M_\odot/Jy (Hildebrand 1983). The total mass detected in our map is then 4.3 \times 10^6 M_\odot. By using an average temperature of 30 K we underestimate the mass in cold regions (GCM0.25+0.01, T = 18 K; Lis & Menten 1988) and overestimate the mass in hot regions (Sgr A CND, T \geq 40K; Davidson et al. 1992).

3.2. Sgr A

The (sub-)millimeter appearance of the molecular clouds in the central 10' of the Galaxy is well known. The SHARC image (Figure 2) of the bright sources GCM–
Table 1. Measured 350 μm Fluxes (Jy)

<table>
<thead>
<tr>
<th>Source</th>
<th>15&quot; beam</th>
<th>30&quot; beam</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 km/s cloud (GCM-0.13–0.08)</td>
<td>294</td>
<td>640</td>
<td>16,000</td>
</tr>
<tr>
<td>50 km/s cloud (GCM-0.02–0.07)</td>
<td>166</td>
<td>370</td>
<td>8000</td>
</tr>
<tr>
<td>CSO-0.14+0.02</td>
<td>73</td>
<td>148</td>
<td>3100</td>
</tr>
<tr>
<td>Sgr A C.N.D.</td>
<td>97</td>
<td>220</td>
<td>1500</td>
</tr>
<tr>
<td>GCM0.07–0.08/GCM0.11–0.08</td>
<td>142</td>
<td>319</td>
<td>13,000</td>
</tr>
<tr>
<td>GCM0.25+0.01</td>
<td>236</td>
<td>523</td>
<td>5900</td>
</tr>
<tr>
<td>Sgr B1</td>
<td>290</td>
<td>625</td>
<td>9300</td>
</tr>
<tr>
<td>Sgr B2 (M)</td>
<td>2740</td>
<td>4740</td>
<td>49,000</td>
</tr>
<tr>
<td>Sgr B2 (N)</td>
<td>2350</td>
<td>3810</td>
<td></td>
</tr>
<tr>
<td>Sgr D</td>
<td>106</td>
<td>197</td>
<td>7600</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>210,000</td>
</tr>
</tbody>
</table>

0.13–0.08 (+20 km/s cloud) and GCM–0.02–0.07 (+50 km/s cloud) reproduces many features observed before at longer wavelengths (Mezger et al. 1996; Lis & Carlstrom 1994; Dent et al. 1993).

The emission from the vicinity of Sgr A* is relatively weak at 350 μm. Sgr A* itself, having a relatively flat submillimeter spectrum (Serabyn et al. 1997), is swamped by dust emission from the 2 pc Circum-Nuclear Disk (CND). The CND, the dominant emitter in the central 10 pc at \( \lambda \sim 100\mu m \) (Odenwald & Fazio 1984; Davidson et al. 1992), is not nearly as prominent in the submillimeter, indicating a lack of cold dust along the line of sight.

An elongated emission feature is visible to the west of GCM–0.13–0.08 running approximately parallel to the Galactic plane. We have labeled the peak of this band as CSO–0.14+0.02. The location and extent of the feature suggest an association with the 'negative velocity arc' observed in \(^{13}\text{CO} \) at \( v = -100 \) to \(-40\) km/s (Bally et al. 1988), although the dust emission appears to be at a slightly more negative Galactic latitude. A far-IR source (Odenwald & Fazio 1984) lies along the arc, so star formation may be occurring in the cloud.

Oka et al. (1999) have recently identified a compact cloud (CO 0.02–0.02) about 5' from Sgr A* with a large velocity width (\( \geq 100 \) km/s). Dust emission in the vicinity of this source is seen in the SHARC map (Figure 2) as well as the maps by Dent et al. (1993), Lis & Carlstrom (1994), and Mezger et al. (1996).

3.3. Radio Arc

Among the prominent 20 cm features in the Galactic center are the Thermal Arched Filaments at \( l = 0.10, b = 0.05 \) (Yusef-Zadeh 1986). The SHARC map of this region is shown in Figure 3. The eastern filament has much more 350 μm emission associated with it than the western filament. The majority of the 350 μm flux is east of the eastern filament, displaced further from the radio features than is the far-IR (50 - 90 μm) emission (Morris, Davidson, & Werner 1995), implying an east (cold) to west (hot) temperature gradient. The 'Arches' star cluster (Cotera et al. 1996; Serabyn, Shupe, & Figer 1998) does not seem well
Figure 2. 350 μm map of Sagittarius A. The contour levels are 40, 60, 80, 100, 140, 180, 220, and 260 Jy/beam. The brightest submillimeter emission is from the 20 km/s and 50 km/s clouds. The fainter Circum-Nuclear Disk is visible partially surrounding Sgr A*. Far-IR sources (Odenwald & Fazio 1984) are labeled with circles.
placed to produce this temperature gradient; a heating source further to the west seems to be required.

A fainter thermal radio filament is located on the opposite side of the Galactic plane, possibly associated with a compact radio feature at $l = 0.100, b = -0.168$. A compact 350 $\mu$m source is detected in this region with a flux of 49 Jy/15" beam, suggesting recent or ongoing star formation.

Oka et al. (1998) find that at 17" resolution, the CO emission from the Galactic center is composed of numerous filaments, arcs and shells. One of the shells, discovered in CS by Tsuboi et al. (1997), may also be seen in the SHARC map.

3.4. Dust Ridge

Lis & Carlstrom (1994) discovered a cold ridge of submillimeter emission extending from GCM0.25+0.10 near the Radio Arc to Sgr B1. The ridge is seen in absorption against the general Galactic center emission at $\lambda \lesssim 70$ $\mu$m (Egan et al. 1998; Lis & Menten 1998). The SHARC 350 $\mu$m map of the Dust Ridge is shown in Figure 4. A fainter ridge of emission is located at negative Galactic latitude, including an extended source at $17^h43^m31.7^s, -28^\circ40'32''$ ($l = 0.330, b = -0.076$) with a peak flux of 77 Jy/15" beam.

3.5. Sgr D

Sgr D is a site of active star formation located at $l = 1.13, b = -0.10$. The projected distance from the Galactic center is 170 pc; however, Sgr D may lie beyond the Galactic center region (Mehringer et al. 1998). The 800 $\mu$m emission from the Sgr D core has previously been mapped by Lis, Carlstrom, & Keene (1991). With SHARC, we have mapped a much larger area and detected diffuse emission over much of the region. The 350 $\mu$m map is compared with the 18 cm map of Mehringer et al. (1998) in Figure 5. The peak flux at the Sgr D core is 106 Jy. To the northwest of the core, the submillimeter emission appears to lie along the boundary of the HII region. Perhaps the radio HII region is density bounded at this position and the submillimeter emission comes from the HII-molecular cloud interface.

Submillimeter emission is associated with both 1.3 cm H$_2$O masers known in the region (Mehringer et al. 1998). Maser source 1 is coincident with the bright Sgr D core, while maser source 2 is associated with a modest (34 Jy/beam) submillimeter source. On the other hand, correspondence of 350 $\mu$m sources with 18 cm OH maser sources is lacking. Of the 4 OH maser sources falling within our map (E, G, H, and I – Mehringer et al. 1998), only one of them (I, coincident with H$_2$O maser 2) has associated submillimeter emission. This supports the suspicion by Mehringer et al. (1998) that sources E, G, and H are evolved stars rather than young stellar objects.

3.6. 350 $\mu$m to 800 $\mu$m Flux Ratio

The large coverage of the 350 $\mu$m SHARC map and the 800 $\mu$m map of Lis & Carlstrom (1994) allows an investigation of the spectral index over the Galactic center region (Figure 6). The mean value of $F_{350\mu m}/F_{800\mu m}$ is approximately 17, which corresponds to a spectral index of $\beta = 2.0$ for 30 K dust. The flux ratio is low (12) at Sgr B2 (N) due to its high optical depth. The flux ratio is
Figure 3. SHARC map of the Radio Arc region. The gray scale and single contours show the 350 μm emission with levels of 25, 50, 75, 100, and 125 Jy/beam. The double contours show 20 cm continuum emission (Yusef-Zadeh 1986). The system of Thermal Arched Filaments – located at 17h42.5m, −28°49′ – lies to the west of a ridge of dust emission while the radio emission from the Sickle (G0.18–0.04) at 17h43.0m, −28°47′ is southeast of a dense cloud. The diamonds mark known clusters of hot stars that may ionize the Filaments and Sickle (Cotera et al. 1996). The partial radio contour at lower left shows two thermal radio filaments at negative Galactic latitude. One of the filaments lies near a compact radio and 350 μm continuum source at 17h43m19.2s, −28°55′16″. Its association with the filament is unknown. The dashed circle shows the rough location of an expanding CS shell discovered by Tsuboi et al. (1997). The shell may also be detected at 350 μm, as suggested by the rounded outer contour, superposed on the ridge formed by GCM0.07–0.08 and GCM0.11–0.08. Circles mark far-IR sources (Odenwald & Fazio 1984).
Figure 4. 350 μm map of Dust Ridge. Contour levels are 25, 50, 75, 100, 175, and 250 Jy/beam. The Dust Ridge lies outside the Radio Arc and consists of a chain of sources extending from the bright elongated cloud GCM0.25+0.01 to Sgr B1. A fainter ridge of sources is located at negative Galactic latitude (eastern part of the map). Three H₂O masers (triangles) have been detected by Lis & Menten (1995); however, the star formation rate in the Dust Ridge as a whole is low. FIR sources (Odenwald & Fazio 1984) are labeled with circles.
Figure 5. SHARC map of Sagittarius D. The gray scale and single contours show the 350 μm emission with levels of 20, 40, and 60 Jy/beam. The double contours show 18 cm continuum measured by Mehringer et al. (1998). The triangles show the positions of H₂O masers, and the plus symbols show OH masers (Mehringer et al. 1998). The H₂O masers correspond more closely with regions of submillimeter emission. The diffuse emission to the northwest of the Sgr D core lies along the boundary of the HII region. The FIR peak from Odenwald & Fazio (1984) is marked with a circle.
Figure 6. Flux ratio $F_{350\mu m}/F_{800\mu m}$. The 800 $\mu m$ map is by Lis & Carlstrom (1994). The 350 $\mu m$ map has been smoothed to 30" resolution to match the 800 $\mu m$ map. The flux ratio is approximately 17 over most of the map. A low spectral index is seen at the cold, optically thick source Sgr B2 (N) at 17$^h$44$^m$10.3$^s$, $-28^\circ 21' 17''$, and a high spectral index is observed at M0.25+0.01 and Sgr B1 in the Dust Ridge. The high spectral index to the east of Sgr B2 and to the west of Sgr A is likely an artifact.
high (27) at GCM0.25+0.01 and Sgr B1 in the Dust Ridge; the large implied $\beta = 2.5$ may be a signature of the lack of high-mass star formation (Lis & Menten 1998; Lis et al. 1998).

Acknowledgments. We thank T. Hunter for assistance in acquiring the data and F. Yusef-Zadeh and D. Mehringer for providing the radio continuum maps. The Caltech Submillimeter Observatory is supported by grant AST 96-15025 from the NSF.

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