THE GALACTIC CENTER IN THE FAR-INFRARED

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ABSTRACT

We analyze the far-infrared dust emission from the Galactic center region, including the circumnuclear disk (CND) and other structures, using Herschel PACS and SPIRE photometric observations. These Herschel data are complemented by unpublished observations by the Infrared Space Observatory Long Wavelength Spectrometer (ISO-LWS), which used parallel mode scans to obtain photometric images of the region with a larger beam than Herschel but with a complementary wavelength coverage and more frequent sampling with 10 detectors observing at 10 different wavelengths in the range from 46 μm to 180 μm, where the emission peaks. We also include data from the Midcourse Space Experiment at 21.3 μm for completeness. We model the combined ISO-LWS continuum plus Herschel PACS and SPIRE photometric data toward the central 2 pc in Sagittarius A* (Sgr A*), a region that includes the CND. We find that the far-infrared spectral energy distribution is best represented by a continuum that is the sum of three gray body curves from dust at temperatures of 90, 44.5, and 23 K. We obtain temperature and molecular hydrogen column density maps of the region. We estimate the mass of the inner part of the CND to be \( \sim 5.0 \times 10^4 \, M_{\odot} \), with luminosities: \( L_{\text{cavity}} \sim 2.2 \times 10^6 \, L_{\odot} \) and \( L_{\text{CND}} \sim 1.5 \times 10^6 \, L_{\odot} \) in the central 2 pc radius around Sgr A*. We find that the Herschel and ISO data that the cold component of the dust dominates the total dust mass, with a contribution of \( \sim 3.2 \times 10^4 \, M_{\odot} \); this important cold material had escaped the notice of earlier studies that relied on shorter wavelength observations. The hotter component disagrees with some earlier estimates, but is consistent with measured gas temperatures and with models that imply shock heating or turbulent effects are at work. We find that the dust grain sizes apparently change widely across the region, perhaps in response to the temperature variations, and we map that distribution.

Key words: dust, extinction – Galaxy: center – infrared: ISM – ISM: individual objects (Sgr A*)

Online-only material: color figures

1. INTRODUCTION

The central \( \sim 1 \) pc of the galaxy is a low density central cavity that surrounds Sgr A*, the compact variable radio source located close to the dynamical center of the Galaxy—a black hole of \( \sim 4.5 \times 10^6 \, M_{\odot} \) at a distance of 8.3 ± 0.4 Kpc (Kerr & Lynden Bell 1986; Ghez et al. 2008; Gillessen et al. 2009). The central cavity is characterized by emission of low ionization atomic species. The cavity contains a cluster of Wolf-Rayet (WR) stars and O and B stars. Using far-infrared (FIR) and submillimeter continuum data, Zylka et al. (1995) estimated that the central cavity (radius \( \sim 1 \) pc) contains \( \sim 400 \, M_{\odot} \) of dust at \( T_{\text{kin}} \sim 40 \) K, \( 4 \, M_{\odot} \) at \( \sim 170 \) K, and \( \sim 0.01 \, M_{\odot} \) at \( \sim 400 \) K. The luminosities emitted by these three phases are \( \sim 2 \times 10^6 \, L_{\odot} \), \( 4 \times 10^6 \, L_{\odot} \), and \( 5 \times 10^6 \, L_{\odot} \), respectively. Latvakoski et al. (1999) studied the region from the Kuiper Airborne Observatory (KAO) in the 30 μm band with a resolution of 8.5' and reported that structures in the region have temperatures ranging from about 70 K to 100 K. They found the total luminosity of the components in the inner region (from their Table 1) to be \( \sim 6 \times 10^6 \, L_{\odot} \) and its mass \( \sim 2000 \, M_{\odot} \).

Surrounding the central cavity, extending from 1 pc to \( \sim 5 \) pc, is the circumnuclear disk (CND). The CND has a mass of several thousand solar masses and rotates with a velocity \( \sim 100 \) km s\(^{-1}\). The neutral material in this ring is clumpy, dense (\( n(H_2) \sim 10^3–10^7 \) cm\(^{-3}\)), and fragmented (Genzel et al. 1982; Genzel & Townes 1987) having a filling factor \( \sim 10\% \) (Zylka et al. 1995; McGary et al. 2001; Wright et al. 2001). There is a clumpy and filamentary structure known as the mini-spiral that connects the CND with the central ionized cavity, allowing ultraviolet radiation from the central ionized cavity to penetrate into the CND, heating and photoionizing the gas (Yusef-Zadeh et al. 2001).

The kinetic temperatures of the gas in the CND and central cavity range as high as 200 K–300 K in CO(\( J = 7–6 \)) (Bradford et al. 2005; Martin et al. 2004) and \( \sim 400 \) K in NH3 (6,6) (Montero-Castaño et al. 2009; Herrnstein & Ho 2005). The source of heating remains unclear. One explanation suggested is that the ionized central cavity is excited by the radiation from a central cluster of O and B stars, and that at the cavity edge the surrounding material is likely to be shock compressed by the expanding gas around the photodissociation regions. Other possibilities include C-shock heating, perhaps by magnetic viscous heating, or possibly turbulent dissipation. Bradford et al. (2005) suggest magnetohydrodynamic (MHD) shock heating with a shock velocity of order 20–30 Km s\(^{-1}\) and a magnetic field of 0.3–0.5 mG. If so, the material in the CND will dissipate its orbital energy within a few revolutions, and they suggest that its apparent longevity may result from refueling by infalling material from the surrounding clouds. Several authors suggest that the ionization of the molecular clouds in the Galactic center is due to a large flux of cosmic rays heating the region (Guesten et al. 1981; Huettemeister et al. 1993; Yusef-Zadeh et al. 2007).

The CND is surrounded by a number of dense molecular clouds and filamentary structures (see Figure 1). At a distance of \( \sim 39 \) pc to the northeast of Sgr A* is the Radio Arc consisting of thermal and nonthermal structures aligned almost perpendicularly to the Galactic plane (Yusef-Zadeh et al. 1984). The Radio Arc seems to connect to Sgr A* via two concentrations of ionized and molecular gas: the Sickle and the Arched Filaments. Two
Figure 1. Composite image of the Sgr A* region: MSX-E at 21.3 μm (blue), 70 μm (green), and SPIRE 350 μm (red). The CND appears more prominent at 21.3 μm and 70 μm due to the lower angular resolution of the 350 μm observations. The black cross shows the position of Sgr A* at R.A. (2000) = 17h45m39.7s77 decl. (2000) = −29°00′43″. A and Q mark the position of the Arches and the Quintuplet clusters of O and WR stars, which provide enough photons to ionize and heat the Sickle and the Arched Filaments. The position of the main molecular clouds (G0.11-0.11, M-0.02-0.07 and M0.25+0.01) across the Galactic center is also indicated. Each tic on the declination axis is an arcminute, corresponding to 2.4 pc. Black contours represent fluxes 0.1, 0.45, 1.0, 1.97, 2.89, 4.0, 5.0, and 14.0 Jy on the PACS 70 μm image.

clusters of WR and O-type stars, the Quintuplet and the Arches Cluster, are responsible for the ionization of the Sickle and the Arched Filaments, respectively. The Arches Cluster is slightly in the foreground, about 20 pc from the Arched Filaments, and irradiates the several filaments approximately uniformly (Lang et al. 2001).

The Midcourse Space Experiment (MSX) image at 21.3 μm and the PACS image at 70 μm trace a shell surrounding the Arches and Quintuplet clusters. The shell goes through the Arched Filaments, the Lima bean, and passes through the south of the G0.11-0.11 molecular cloud forming a ring of ~44 pc in diameter (Figure 1). Bally et al. (2010) suggest that the radiation and the stellar winds from the Arches and the Quintuplet clusters and the black hole in Sgr A* may be responsible for the formation of this shell, which can clearly be seen in the Spitzer 24 μm image (Yusef-Zadeh et al. 2009), and which has also been reported by Moneti et al. (2001).

Recent studies by Molinari et al. (2011), using far-infrared images obtained with the Herschel PACS and SPIRE instruments, reveal the presence of a 100 × 60 pc elliptical loop shaped by a chain of cold and high column density clumps ($T_{\text{dust}} \leq 20$ K; $N(\text{H}) > 2 \times 10^{23}$ cm$^{-2}$) orbiting around the Galactic center. The loop is shifted with respect to the Galactic center with Sgr B and Sgr C placed close to the two ends of the 100 pc semi-major axis, and Sgr A* at a projected distance of 24 pc toward the negative semi-major axis. Herrnstein & Ho (2005) suggested that Sgr A* is interacting with the M-0.02-0.07 molecular cloud (Figure 1) which indicates that Sgr A* is probably closer to the front of the loop than to the back (Molinari et al., 2011).

The objective of this paper is to further constrain the physical conditions in the central 2 pc of the Galactic center and to help clarify the excitation conditions. We use archival Herschel PACS and SPIRE photometric observations of the region to determine the dust properties more accurately; many earlier data sets at shorter wavelengths (Latvakoski et al. 1999) would have been insensitive to a cold dust component. We also incorporate previously unpublished infrared images from the Infrared Space Observatory Long Wavelength Spectrometer (ISO-LWS), operating in parallel mode; its grating sampling allows us to obtain a more precise analysis of the character and structure of dust in the central region and the CND.

2. OBSERVATIONS

Herschel PACS (Poglitsch et al. 2001) data at 70 μm and 160 μm, and SPIRE (Griffin et al. 2006) data at 250 μm, 350 μm, and 500 μm, were used to measure the dust temperature and the column density distribution across the Galactic center region. The basic data were obtained from the public Herschel archive and were reprocessed using HIPE, the Herschel Interactive Processing Environment. The data were collected in parallel mode and are still rather preliminary in absolute accuracy, suffering from calibration errors. PACS fluxes off the bright Galactic
Table 1

| $\lambda$ ($\mu$m) | PACS | SPIRE |
|-------------------|-------|-------|
|                   | 70.0  | 160.0 |
|                   | 250.0 | 350.0 |
|                   | 500.0 |
| Pixel ("')        | 2.0   | 3.0   |
| FWHM ("')        | 5.9   | 11.6  |
| FWHM (pc)        | 0.24  | 0.48  | 0.76  | 1.04  | 1.52  |

plane are negative, indicating that the pipeline corrections are inaccurate; moreover, there are indications that in this extremely bright region some nonlinear detector responses are uncorrected. We do not apply any across-the-board offsets to get positive flux values. As a result, the derivative images we discuss below are reliable over most but not all of the area, but the spectral energy distributions (SEDs) we fit to the warm central region (see Section 4) are accurate. Images are made in Jy pixel$^{-1}$ at 2′0 pixel$^{-1}$ and 3′0 pixel$^{-1}$ for PACS 70 $\mu$m and 160 $\mu$m, respectively, and in Jy beam$^{-1}$ for SPIRE data at 250, 350, and 500 $\mu$m, with beam areas, respectively, of 395$''$$^2$, 740$''$$^2$, and 1571$''$$^2$ (PACS and SPIRE pixel and beam sizes are given in Table 1). Figure 1 covers an area of 28.46 $\times$ 29.4 arcmin$^2$ centered at R.A.(2000) = $17^h45^m39.77^s$, decl.(2000) = $-29^\circ00'43''.0$. For a distance of 8.5 kpc, the covered area is $\sim 70.4 \times 72.7$ pc$^2$.

The image is color-stretched to show more of the faint or cool structures, which are labeled. The most obvious places where the photometry issues make analyses difficult are in the coldest, dark regions, for example, in G0.11-0.11. We white-out the corresponding area in the derivative column density and spectral index images because of the uncertain correction to the negative fluxes reported by the current Herschel pipeline.

The MSX surveyed the Galactic plane at six bands from 4.2 to 26 $\mu$m at a spatial resolution of 18′ (Egan et al. 1999). The MSX data can also be used to study the morphology, dynamics, and physics of the interstellar medium providing the thermal emission from dust grains at mid-infrared wavelengths (Cohen and physics of the interstellar medium providing the thermal emission from dust grains at mid-infrared wavelengths (Cohen 1999). We used the MSX Band E data at 21.3 $\mu$m to trace the warm dust across the Galactic center.

We also report in this paper previously unpublished observations of Sgr A* taken by the LWS (spectral range 46–180 $\mu$m) on the ISO satellite in parallel mode. ISO was equipped with two spectrometers, the Short Wavelength Spectrometer and LWS, a camera, ISOCAM, and an imaging photopolarimeter, ISOPHOT, to cover wavelengths from 2.5 to 240 $\mu$m with spatial resolutions of 1.5′ at the shortest wavelengths and 85′–90′ at the longer wavelengths. Two instruments, LWS and ISOCAM, were able to operate simultaneously in parallel mode. More than 100,000 individual pointings were made in parallel mode in over 17,000 individual observations with a total sky coverage of about 1%. Key to our study, the LWS operated with 10 wavelengths in the range 46–180 $\mu$m (Lim et al. 2000), each with bandwidths of about 0.3 $\mu$m for the five short wavelength (SW) detectors and 0.6 $\mu$m for the five long wavelength (LW) detectors. Parallel mode maps are generated by combining different raster scans. Several data reduction tools were developed in the IDL programming language and these form the LWS parallel interactive analysis package that can be found at http://www.ipac.caltech.edu/iso/lws/lia/lia.html.

Now that the Herschel observations have obtained longer wavelength coverage, out to 500 $\mu$m, the earlier ISO data can reliably be combined with them to prepare a more comprehensible picture. In particular, the spectral information obtained with ISO-LWS allows us to determine the peak wavelength and flux of the dust emission with much greater precision than is possible with broadband photometry; this in turn allows us to specify the conditions of excitation much more accurately.

3. DUST GRAIN PROPERTIES: TEMPERATURE AND OPTICAL DEPTH MAPS

Herschel PACS and SPIRE photometry have a much higher spatial resolution in the FIR than any previous mission. When analyzed, the maps provide a much improved spatial distribution of the fluxes, temperature, spectral index, and $H_2$ column density across the Galactic center region. The MSX 21.3 $\mu$m images provide an important measure of the warmer material in the region. Figure 1 shows the Galactic center as seen by combined images of MSX-E 21.3 $\mu$m (blue), PACS 70 $\mu$m (green), and SPIRE 350 $\mu$m (red). The Arched Filaments, the Radio Arc, and Sgr A* are clearly visible at 21.3 $\mu$m and 70 $\mu$m, while SPIRE 350 $\mu$m traces the very cold and dense molecular clouds. Herschel resolves the central cavity and the surrounding CND at 70, 160, and 250 $\mu$m; the lower SPIRE 350 and 500 $\mu$m resolutions (FWHM = 25′.3 and 36′.9, respectively) are not quite able to resolve the cavity.

The observed continuum emission from the Galactic center region peaks at about 66 $\mu$m, in the range of ISO-LWS detector SW3 (Figure 2). As shown in Figure 2, the shape of the SED cannot be fit by a single gray body curve. In the ensuing discussion, we present our procedure for decomposing the shape, which depends on the temperature, the number of grains along the line of sight, and their emissivity and spectral index, $\beta$. At the longest wavelengths, the grain properties determine the shape of the SED. We assume a grain size of $a \sim 0.1$ $\mu$m. The temperature and the spectral index, $\beta$, distribution across the Galactic center were then obtained by fitting the PACS and SPIRE wavelengths with a gray body curve:

$$F_\nu = \Omega \times B_\nu(T) \times (1 - e^{-\tau_\nu}),$$  

(1)

where $\Omega$ is the solid angle, $T$ is the temperature, and $\tau_\nu$ is the optical depth for a frequency $\nu$, given as

$$\tau_\nu = \tau_0 \left( \frac{\nu}{\nu_0} \right)^\beta,$$  

(2)

with $\tau_0$ the reference optical depth at $\nu_0$, the reference frequency, which was chosen to be $c/100$ $\mu$m. The shape of the curve is only mildly sensitive to the choice of $\nu_0$ (Lewis & Chapman 2000).

The SED for each pixel in the Herschel image was fitted after smoothing the images and adjusting the pixel sizes uniformly to the resolution of the SPIRE 500 $\mu$m channel band. The $H_2$ column density was then derived assuming a gas-to-dust-ratio of 100. We did not include the PACS 160 $\mu$m image data with the other four Herschel bands in the calculation of the temperature and the column density maps.

At the brightest regions, the flux values from this detector did not fit any physical SED, perhaps due to a poor correction of low level stripes in the data and/or errors on the background subtraction. Moreover, in the low intensity regions the detector map has negative values possibly due to uncorrected gain adjustments (Bernard et al. 2010). Its omission will not affect the conclusions significantly; subsequent pipeline reductions will hopefully address these issues.
The Astronomical Journal, 142:134 (9pp), 2011 October

Etxaluze et al.

Figure 2. Top: integrated fluxes in the ISO-LWS beam for each detector (black triangles) centered at the position of Sgr A*. The continuum is fitted by the sum of three different dust components: (blue) a very hot \( T_{\text{dust}} = 90 \) K with a very low density component \( n_{\text{H}_2} \sim 2.8 \times 10^3 \) cm\(^{-3}\) arising from the central cavity, and two different dust components coming out from the inner part of the CND, (green) a hot component \( T_{\text{dust}} = 45 \) K with a density of \( n_{\text{H}_2} \sim 1.19 \times 10^4 \) cm\(^{-3}\), and (red) a cold component \( T_{\text{dust}} = 23.5 \) K with very high density \( n_{\text{H}_2} \sim 2.41 \times 10^4 \) cm\(^{-3}\). The gray line represents the total contribution. Bottom: the continuum extended to longer wavelengths. The black squares represent the Herschel fluxes integrated on the ISO-LWS beam at each detector: PACS at 70 \( \mu \)m, and SPIRE at 250, 350, and 500 \( \mu \)m. (A color version of this figure is available in the online journal.)

Figures 3–5 show the resultant temperature, molecular hydrogen column density, and \( \beta \) maps, respectively; north is up in all cases. The white circle on the temperature map, centered at Sgr A*, shows the average size of the ISO-LWS beam which covers, approximately, the central cavity and the inner 1 pc of the CND, for a distance to the region of 8.5 kpc. Figure 7 shows the PACS 160 \( \mu \)m map; although the absolute calibration is defective, as noted, its higher resolution provides an improved picture of the CND than does either the temperature or column density maps, which have been reduced to the SPIRE 500 \( \mu \)m beam size and are therefore unable to resolve the CND and cavity structure.

3.1. The Temperature Map

The temperature map (Figure 3) shows the most distinguishing details of the various structures in this complex region. As expected, due to the strong UV radiation and the stellar winds from the WR and the OB stellar clusters placed at the central cavity, as well as the electron heating due to MHD turbulences that take place in accretion states around the central black hole (Liu et al. 2011), Sgr A* shows the highest temperature values, where \( T_{\text{dust}} \gtrsim 60 \) K.

This map beautifully resolves the Arched Filaments and Sickle with dust temperatures \( T_{\text{dust}} \sim 35 \) K, and the Radio...
Arc, with significantly lower temperatures than the Arched Filaments: $T_{\text{dust}} \sim 28$ K. As expected, the coldest region in the temperature map occurs in the giant molecular cloud G0.11-0.11, whose temperatures are $T_{\text{dust}} \lesssim 18$ K. As we discuss in more detail below and in Figure 8, these results are in agreement with the ISO-LWS images, in which the Arches (for example) fade away as the wavelength changes from 46 μm to 178 μm. Morris et al. (1995) used the KAO at 50 μm and 90 μm to map this region. They infer a dust temperature for the Arches of 45–55 K using a $\beta = 1$, which is noticeably warmer and inconsistent with our result, in some part because $\beta$ is actually closer to 2.

Colgan et al. (1996) reported that the more eastern filament (called E2) might even be higher than 70 K. The new *Herschel*-ISO results show that there is considerable knotty structure along each of the filaments and elsewhere across the region, but that average dust temperatures are more accurately closer to 35 K.

### 3.2. The Column Density Map

The column density map (Figure 4) reveals the presence of numerous dense features, most of which have been previously reported. Bally et al. (2010) discuss many of them based on their SHARCII 0.35 mm and BOLOCAM 1.1 mm continuum images with a resolution of 9′′ and 33′′, respectively.

Figure 4 shows only about a factor of 10 variations across most of the region, with few distinct structures being defined by their high column densities. The exception is the well defined, very dark cloud G0.11-0.11 with very low dust temperature, between 12 K and 18 K, and whose peak column densities exceed $N$(H$_2$) $\gtrsim 3.0 \times 10^{23}$ cm$^{-3}$. By contrast, the total luminosity varies as $T^{4+\beta}$ across the region, in which $\beta$ changes from about 1 to 3, and the dust surface brightness varies by a factor of about 300 even in the less dense structures. The column density map closely anti-correlates with the temperature map, with denser regions being colder.

As a result of the low fluxes, as noted earlier, the PACS photometry in the area of G0.11-0.11 has uncorrected negative values, and the density and $\beta$ values are only approximate. In Figures 4 and 5, the scale has been intentionally stretched to highlight the less prominent structures at the expense of saturating the G0.11-0.11 area. The cloud itself is more accurately defined by the SPIRE emission (see Figure 1, in red), and indeed the images reveal considerable knots and substructure across the source. The southerly extension to the source, visible in the three derived maps, is an artifact of the negative photometry in the low flux region; SPIRE emission clearly shows that the low flux is due to an absence of material rather than cold high density dust. We can nevertheless estimate a lower limit to the total mass of G0.11-0.11 as $1 \times 10^6 M_\odot$.

### 3.3. The Spectral Index Map

The map for $\beta$ is shown in Figure 5; it is also anti-correlated with the temperature map (Figure 3). Sgr A*, for example, the hottest region, shows the lowest values of $\beta \sim 1.0$–1.3. The Arched Filaments and Sickle show values in the range $\beta \sim 1.3$–1.8 and the range of $\beta$ values in the Radio Arc is $\beta \sim 1.7$–2.2. The G0.11-0.11 molecular cloud shows extremely large values of $\beta \sim 3.5$. This general trend was observed by Dupac et al. (2003) in a variety of regions in the ISM, and by Boudet et al. (2005) in the laboratory for amorphous compounds. Whether this anticorrelation between $\beta$ and the temperature is due to averaging different values of temperature along the line of sight or due to quantum physics effects on the amorphous grains is something that remains uncertain. More laboratory measurements would be necessary in order to study other possible causes such as the fact that the grain size varies in different environments, and that the chemical composition of the grains shows a large variation from region to region (Hirashita et al. 2007; Butler & Tan 2009).

Since the total luminosity varies roughly as $T^{4+\beta}$, this parameter also helps sort out the excitation and energetics of the various structures. The anti-correlation between temperature and density applies to most of the other dense regions of the maps as well, which, being dominated by dust properties, are coldest where they are most opaque (Figure 4); for example, through the Arched Filaments, Sickle, the Radio Arc, and Sgr A*.

### 3.4. The Distribution of the Very Small Grains

The O and WR stars from the Arches and the Quintuplet clusters (Figure 1) provide enough photons to ionize and heat the Sickle and the Arched Filaments (Cotera et al. 1996) and also generate strong winds that could contribute to the depletion of the largest dust grains whose population is traced by the $N$(H$_2$) map. The largest dust grains can be destroyed due to the strong winds and the UV radiation from the massive O and WR stars from the Arches and Quintuplet clusters.

The MSX-$E$ map at 21.3 μm (Figure 6) can be used to trace the population of very small grains (VSGs) throughout the Galactic center region (this band is more reliable than the features observed at shorter infrared wavelengths which can be affected by extinction). VSGs are small (with sizes of $\sim 0.01$ μm), and absorption of one UV photon (Pomarés et al. 2009) can increase their temperature up to 80 K, prompting them to re-emit at these shorter wavelengths ($\lambda \sim 24$ μm; Desert et al. 1990;
Boulanger et al. 1985). The MSX map correlates well with the temperature map, showing that the population of the small grains is distributed through the regions where the population of the largest grains has been depleted, i.e., the Sickle and the Arched Filaments. This effect can also be observed in Sgr A*: PACS 160 μm, Figure 7, shows very low emission at this far-infrared wavelength in the central cavity of Sgr A*, but it is surrounded by bright emission from the CND. The emission in the inner parsec, as traced by MSX-E at 21.3 μm, appears confined to the central cavity where the O and B stars from the central cluster produce a strong radiation field, and where stellar winds heat up the small grains and deplete large grains. Within the central 2 pc, the largest grains are found remaining in the CND itself, where they are shielded from the central strong UV radiation; their emission is traced by Herschel PACS+SPIRE at far-infrared wavelengths λ > 60 μm.

4. THE TEMPERATURE COMPONENTS OF THE CND: FITTING THE ISO-LWS CONTINUUM

ISO-LWS obtained images of the central region of the galaxy operating in its parallel mode, one image simultaneously from each of the 10 ISO-LWS detectors, with the spectrometer’s grating set at a fixed position near the center of its scan range. The ISO-LWS parallel mode maps provide us with complementary wavelength coverage just where it is most needed, at the peak of the dust emission, in the range of 46–180 μm that can be used to defined the SED of Sgr A* at far-infrared wavelengths. Unfortunately, with a beam of ~85″ and a pixel size of 42″, these ISO maps are unable to resolve as many structures as do higher resolution Herschel PACS and SPIRE data.

Figure 8 shows the resultant Galactic center images in each of the 10 bands. The images are centered at R.A. (2000) = 17h45m56.5s, decl. (2000) = −28°55′15″24 and cover an area of ~22.8 × 29.6 arcmin² (~59 × 77 pc²). In order to obtain accurate photometry from these images, an extended source flux correction factor is required, as described in the ISO Users Manual. Fortunately, we also had pointed observations with which to confirm the correction procedure (see G. J. White et al. 2011, in preparation for a description of the ISO pointed photometric and spectroscopic observations). The observed flux in Jy is

\[ S_\nu (\text{Jy}) = F_\nu \times \frac{f}{(\Omega \times 10^6)} \text{(MJy sr}^{-1}) \],

and the extended source correction factors \( f \) and the solid angle \( \Omega \) are given in Table 2. Besides, Casassus et al. (2008) reported that the ISO-LW1 at 102.42 μm intensities were 27% higher than IRAS 100 μm for intensities below 1000 MJy sr⁻¹ and 40% higher for intensities above 1000 MJy sr⁻¹. This was in agreement with Chan et al. (2003). This offset on the ISO parallel mode data was calculated by comparing the fluxes at different position along the Galactic center observed in primary mode with the fluxes observed in parallel at the same position for the 10 ISO-LWS detectors. The correction factors, \( Q(\text{Flux}_{\text{parallel}}/\text{Flux}_{\text{primary}}) \), are also given in Table 2.

Despite the correction factors were applied, the LW2 fluxes still seem to be offset in our data by 10% above the continuum level. Due to this problem, the LW2 flux was omitted when fitting the ISO-LWS SED in Figure 2.

Sgr A* is very bright at the shortest wavelengths and clearly seen in Figure 8. The SW detectors (46.2–84.79 μm) also show the northern part of the Radio Arc. Detectors SW4 75.69 μm, SW5 84.79 μm, LW1 102.42 μm, and LW2 122.2 μm show Sgr A* as a single object about ~4 pc in radius that includes Sgr A* and extends to the M-0.02-0.07 molecular cloud (Figure 1) in the south. At 160.55 μm (LW4) and 177.97 μm...
Figure 8. Galactic center observed at each ISO-LWS parallel mode wavelength: 46.222 μm (SW1), 56.2033 μm (SW2), 66.1175 μm (SW3), 75.6989 μm (SW4), 84.7977 μm (SW5), 102.425 μm (LW1), 122.218 μm (LW2), 141.809 μm (LW3), 160.554 μm (LW4), and 177.971 μm (LW5). Black contours on SW3 are PACS 70 μm convolved with the SPIRE 500 μm beam size (36′′) and the black contours on LW4 correspond to PACS 160 μm emission with a beam size of 36′′.9. The black circle on the SW1 map represents the ISO-LWS beam (∼3.5 pc) centered at the position of Sgr A*.

(A color version of this figure is available in the online journal.)

Table 2

| Detector | λ (μm) | f | Ω × 10^6 (sr) | Q |
|----------|--------|---|---------------|---|
| SW1      | 46.22  | 0.8704 | 0.1140 | 1.082 |
| SW2      | 56.20  | 0.8677 | 0.1321 | 0.899 |
| SW3      | 66.11  | 0.8421 | 0.1410 | 0.889 |
| SW4      | 75.69  | 0.7334 | 0.1223 | 0.823 |
| SW5      | 84.79  | 0.6787 | 0.1163 | 0.878 |
| LW1      | 102.42 | 0.6758 | 0.1111 | 0.930 |
| LW2      | 122.21 | 0.6734 | 0.1128 | 0.823 |
| LW3      | 141.80 | 0.6035 | 0.0935 | 0.948 |
| LW4      | 160.55 | 0.5411 | 0.0904 | 0.992 |
| LW5      | 177.97 | 0.4596 | 0.0833 | 1.004 |

The most conspicuous feature is the cold and dense molecular cloud M-0.02-0.07 (see also Figure 1).

The SED of Sgr A* within the ∼85″ ISO-LWS beam is shown in Figure 2. Each data point in Figure 2 represents the integrated flux on the ISO-LWS beam centered at the position of Sgr A* at each wavelength. We note that at a distance to the region of about 8.5 kpc, the ISO-LWS beam size of 3.5 pc includes the central cavity and the inner ∼0.8 pc of the CND, not quite large enough to completely include the full CND observed in the Herschel maps. In order to model the ISO-LWS continuum spectrum across the wavelength range ∼40–200 μm, we assumed typical dust properties: dust grains of 0.1 μm in radius and a bulk density of 2.5 (g cm⁻³). These values are characteristic of silicate grains that contain H₂O inside their structures (e.g., Pollack et al. 1994). The dust opacity is defined as

\[ \kappa_{\lambda} \cdot \rho = \frac{\kappa_{\text{const}}}{\lambda^\beta}, \]

where \( \kappa_{\lambda} \) (cm² g⁻¹) is the dust opacity, \( \rho \) (g cm⁻³) is the bulk density of the grains, and \( \kappa_{\text{const}} \) is a proportionality constant. For \( \lambda = 100 \) μm and \( \kappa_{\text{const}} = 0.8 \) the dust opacity in the central cavity is \( \kappa_{100 \mu m} \sim 92 \) cm² g⁻¹, characteristic of dust grains with thin ice mantles, while the opacities at the CND are ∼160 and 200 cm² g⁻¹ for the hot and the cold component, respectively. These values are typical of dust grains with thick ice layers (Ossenkopf & Henning 1994).

The best model that we found able to reproduce the LWS spectral continuum consists of three temperature components: an SED arising from the central cavity of \( r = 1 \) pc in radius, and a combination of a warm plus cold SED arising from the inner 0.86 pc of the CND. Figure 4 shows the steep gradient in column density at the position of Sgr A* from values of \( N_{\text{H}_2} \sim 3 \times 10^{22} \) cm⁻² at the center of the cavity to higher values \( \sim 1 \times 10^{23} \) cm⁻² at the CND. The temperature map (Figure 3) likewise shows the largest values just on the center, \( T_{\text{dust}} \gtrsim 60 \) K, surrounded by colder dust. The SED from the cavity can be fitted by a gray body curve defined by a dust temperature of \( T_{\text{dust}} = 90 \) K, \( \beta = 1.23 \), and a low column density of \( N_{\text{H}_2} = 8.73 \times 10^{21} \) cm⁻².

As noted, the SED of the CND requires two components in order to fit the whole ISO-LWS continuum: a hot component of \( T_{\text{dust}} = 44.5 \) K, \( \beta = 1.35 \), and a column density of \( N_{\text{H}_2} = 3.18 \times 10^{22} \) cm⁻². Significantly, a cold component also has to be introduced in order to fit the longest wavelengths of the ISO-LWS data. The cold component can be fitted by a \( T_{\text{dust}} \)
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5. CONCLUSIONS

We present new Herschel PACS and SPIRE maps of the Galactic center, together with previously unpublished ISO-LWS 10 band parallel mode maps that enable us to obtain an accurate calibration for the central parsecs and a detailed spectral shape around the wavelength peak of the continuum emission. Photometry from the data set allows us to model dust in the central 2 pc of the Galactic center. Combined with MSX-E 21.3 μm images, we use these new results to trace the dust properties throughout the Galactic center region.

The ISO-LWS continuum in the direction of Sgr A*, extended with Herschel data out to 500 μm, is best fit by a model of a central cavity of 1 pc radius emitting like a gray body with $T = 90$ K and $\beta = 1.23$ and with low density $n(H_2) = 2.8 \times 10^3$ cm$^{-3}$. The region is surrounded by the CND represented by two different components: a hot component with a dust temperature of 44.5 K and $n(H_2) = 1.19 \times 10^4$ cm$^{-3}$ with $\beta = 1.35$, and a cold component with $T_{dust} = 23.5$ K, $n(H_2) = 2.41 \times 10^3$ cm$^{-3}$, and $\beta = 1.4$. The two components indicate that the CND is not a single uniform body, but (as suggested by the images and previous authors) has numerous clumps, gaps, and substructures but whose average properties manifest these two basic behaviors. This simple model is able to reproduce the observed ISO-LWS continuum as well as the SPIRE data at 250 μm, 350 μm, and 500 μm. The MSX-E map traces the emission of the VSG population through the Radio Arc, the Sickle, and the Arched Filaments, and that confined in the central cavity in Sgr A*. These spatial structures are now directly detected in the far-infrared, and, with the full SED available, their dust features are all characterized. As expected, the largest grains are distributed throughout the CND and correspond to the densest and coolest molecular clouds. Unresolved issues with the Herschel photometry in the current data set leave the absolute accuracy of the coldest, densest regions (like G0.11-0.11) approximate.

Dust opacity properties in the central cavity are typical of grains with a thin ice layer while the dust properties in the CND, with lower temperatures and the highest densities, are more typical of dust grains with thick ice mantles.

The total integrated continuum flux around the inner edge of the CND and the central cavity provides a total mass of $M \sim 4.9 \times 10^4 M_\odot$. The luminosities obtained are $L_{cavity} \sim 2.2 \times 10^6 L_\odot$ and $L_{CND} \sim 1.5 \times 10^6 L_\odot$ in the central 2.0 pc in Sgr A*.

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Table 3

| Physical Parameters | Cavity | CND$_{hot}$ | CND$_{cold}$ |
|---------------------|--------|------------|-------------|
| Radius (pc)         | 1.0    | 0.86       | 0.86        |
| $\beta$             | 1.23   | 1.35       | 1.40        |
| $\kappa_{const}$    | 0.8    | 0.8        | 0.8         |
| $\kappa_{dust}$     | 0.8    | 0.8        | 0.8         |
| $T_{dust}$ (K)      | 90.0   | 44.5       | 23.5        |
| $\delta_{dust}$ (cm$^{-3}$) | $9.45 \times 10^{-23}$ | $4.0 \times 10^{-22}$ | $8.05 \times 10^{-22}$ |
| $\tau_{00, \mu m}$  | $5 \times 10^{-3}$ | $3 \times 10^{-2}$ | $8 \times 10^{-2}$ |
| $N_{H_2}$ (cm$^{-2}$)| $8.73 \times 10^{21}$ | $3.18 \times 10^{22}$ | $6.39 \times 10^{22}$ |
| $n_{H_2}$ (cm$^{-3}$) | $2.8 \times 10^{4}$ | $1.19 \times 10^{4}$ | $2.41 \times 10^{4}$ |
| $\chi^2_{dust}$     | 0.01   | 0.01       | 0.01        |
| $L (L_\odot)$       | $2.2 \times 10^{6}$ | $1.4 \times 10^{6}$ | $1.0 \times 10^{6}$ |
| $M (M_\odot)$       | $1.7 \times 10^{4}$ | $1.56 \times 10^{4}$ | $3.15 \times 10^{4}$ |

= 23.5 K modified blackbody with $\beta = 1.40$ and a higher column density $N(H_2) = 6.39 \times 10^{22}$ cm$^{-2}$. This massive new cold component, previously unreported in observations done only at shorter wavelengths, is confirmed by the longer wavelength Herschel photometry. This simple, three-component model reproduces very well the observed continuum emission at the ISO-LWS spectrum (Figure 2) and the SPIRE and PACS 70 μm data. The luminosity of each component is $L_{cavity} \sim 2.2 \times 10^6 L_\odot$, $L_{CND} \sim 1.4 \times 10^6 L_\odot$, and $L_{CND} \sim 1.0 \times 10^6 L_\odot$, and the total gas mass: $M_{cavity} \sim 1.7 \times 10^3 M_\odot$, $M_{CND} \sim 1.56 \times 10^4 M_\odot$, and $M_{CND} \sim 3.15 \times 10^4 M_\odot$. Table 3 lists the parameters from the fit to the ISO-LWS continuum.

The flux errors on the ISO-LWS data are 10%–15% (Gry et al. 2003). Assuming an error of ~12% for each detector, the goodness of the fit in Figure 2 is $\chi^2 = 0.89$ (LW2 flux was not taken into account on the estimation of $\chi^2$). The CND cold component has to be included in the model in order to fit accurately the SPIRE fluxes at wavelengths $\geq 250 \mu m$. Models with just one CND component can also reproduce the ISO-LWS continuum very precisely. However, the model must satisfy another constraint set by the fluxes of the atomic and molecular lines detected by ISO-LWS in this region. We have used a radiative transfer code as described in González-Alfonso et al. (2002) to simultaneously fit the continuum and the spectral lines, obtaining the best results for the case of two CND components. We present the discussion of the gas properties through Sgr A* in a separate paper (G. J. White et al. 2011, in preparation).

The Astronomical Journal, 142:134 (9pp), 2011 October

Etxaluze et al.
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