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RESEARCH PAPER

Complex magnetic field of the extreme Galactic Center: PRIMA science potential

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ABSTRACT. The Central Molecular Zone (CMZ) of the Galactic Center (GC) region of the Milky Way contains a substantial fraction of the molecular mass of the Galaxy ($\geq 10^7\ M_\odot$) yet exhibits an order of magnitude lower star formation efficiency (SFE) than expected given the high densities found in this region. There are multiple possible explanations for the depressed SFE in the CMZ, such as feedback, strong turbulence, longer free-fall timescales, and high magnetic field strengths. It is currently unclear which of these mechanisms is the dominant inhibitor of star formation in the CMZ. It is important to understand the star formation process in the extreme environment of the CMZ because it is the only Galactic nuclear region we are able to study at high spatial resolutions with current observatories. One way to determine the relative importance of the different SFE inhibiting mechanisms is through multi-spatial and multifrequency polarimetric observations of the CMZ. Such observations will provide insight into the behavior of the magnetic field in this unique environment. These observations will complement radio observations of nonthermal structures revealing the magnetic field morphology and polarization. The Probe far-Infrared Mission for Astrophysics (PRIMA) will be uniquely capable of contributing to such explorations by providing unique resolutions and frequencies for polarimetric observations. The PRIMAger instrument will yield polarimetric observations covering the wavelength range 80 to 261 μm with beam sizes ranging from 11 to 28″, capabilities that complement existing and upcoming observatories.

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1 Introduction

The central region of the Milky Way, known as the Central Molecular Zone (CMZ), contains 4% (or $\geq 10^7\ M_\odot$) of the molecular mass of the Milky Way.[1] The CMZ consists of numerous high density clouds (with densities ranging from 10^3 to 10^6 cm^{-3}), elevated turbulent linewidths (10 to 50 km s^{-1}), and strong magnetic field strengths of 100s of μG even in low density portions of the CMZ.[2–5] Figure 1 displays the CMZ as probed by infrared and radio observations revealing

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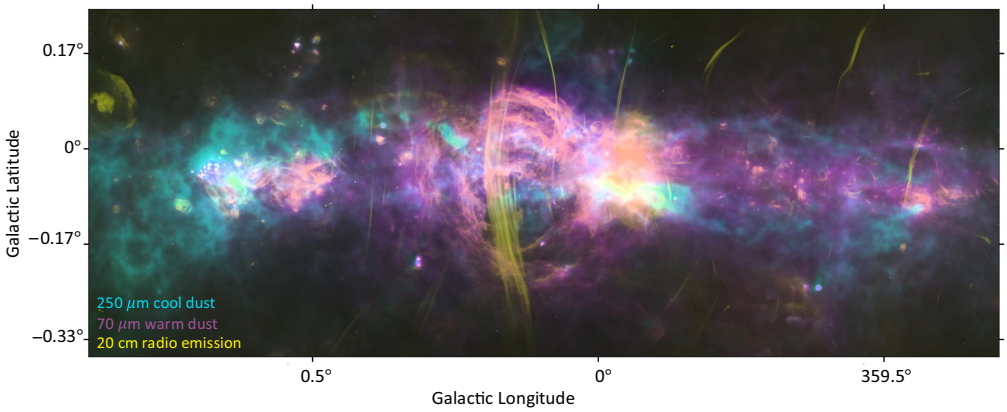


Fig. 1 Three-color view of the CMZ[6] with 20 cm (1.28 GHz) MeerKAT radio emission in yellow and 250 μm cool dust and 70 μm warm dust emission in cyan and magenta, respectively, both observed by Herschel.[7,8]

the complex thermal and nonthermal structures observed in the region.[6] Many of the nonthermal features are organized as filamentary structures collectively known as the nonthermal filaments (NTFs). The NTFs shown in the radio emission in Fig. 1 are unique to the GC and imply the existence of a CMZ-wide vertical magnetic field oriented perpendicular to the Galactic disk. The magnetic field inferred from far-infrared dust polarization is, conversely, observed to be a horizontal field oriented parallel to the Galactic disk.[9] The complexity of the magnetic field in this region indicates that the magnetic field in this region may be of particular dynamical importance.

The extreme conditions of the CMZ, coupled with its relative proximity to Earth (being only ∼8 kpc away[10]), make it an important local analog to more distant galactic nuclear regions. Observations of the CMZ can therefore provide insight into structures such as the individual molecular clouds present within a galactic nuclear region. The star formation efficiency (SFE) in the CMZ is only 10% of that which would be expected given the high densities found there (predicted star formation rate of $\sim 0.5\,M_\odot\,yr^{-1}$ compared with an actual star formation rate of $\sim 0.02\,M_\odot\,yr^{-1}$).[3,11,12] There are multiple possible explanations for the low SFE in the CMZ, which include the high strength of the magnetic field, high velocity gradients caused by strong tidal forces, plasma compressibility as a result of the high field strengths, and elevated turbulence.[13] Understanding how each of these factors is inhibiting star formation in the GC will expand our understanding of the properties of star formation in extreme environments such as the CMZ and other galactic nuclear regions.

The magnetic field in the molecular component in this region can be probed at sub-millimeter and far-infrared wavelengths using dust polarization observations. Dust grains in the presence of a magnetic field are preferentially aligned with their long axis perpendicular to the orientation of the field, resulting in the thermal emission of light polarized with an orientation perpendicular to the plane-of-sky magnetic field direction. The favored mechanism is known as radiative torque alignment.[14,15] In the proceeding discussion and throughout the paper, we assume that the dust grains in the CMZ are aligned by this mechanism.

One way to assess the impact of the magnetic field strength and turbulence on star formation is to study the structure of magnetic fields in different physical environments over multiple spatial scales ranging from, for example, protostellar core scales (1000s of AU, or ∼5 mpc) to molecular cloud scales (100,000 AU, or ∼0.5 pc).[16] Such multiscale analyses have been conducted in the Galactic disk for numerous star-forming regions.[17] For example, the magnetic field of the star forming region Ser-emb-8 was studied over a range of spatial scales from 100 to 10,000 AU (5×10^{-4} to 5×10^{-2} pc), and it was determined that the turbulence of the cloud was more significant in inhibiting star formation than the magnetic field.[18] The multispatial observations applied to that source are shown in Fig. 2. The conclusion that turbulence dominates over the magnetic field for this star forming region was reached because of the disconnect observed between the magnetic field configuration encountered over a broad range of spatial scales. Such a disconnect was also predicted from magnetohydrodynamic (MHD) simulations of this source,

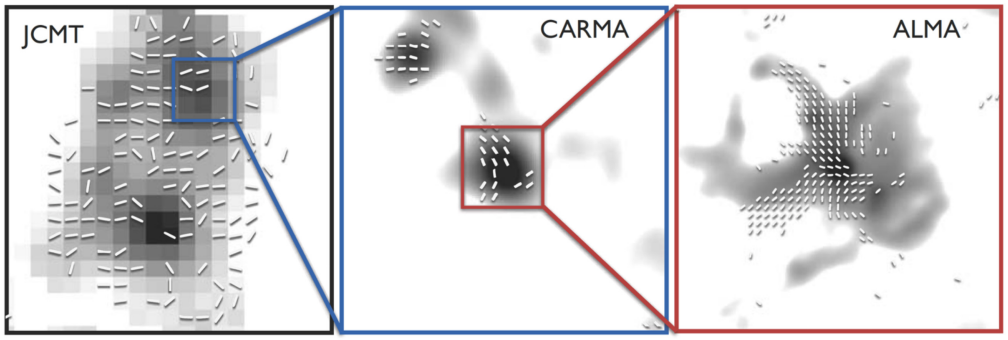


Fig. 2 As an example of a multiscale magnetic field analysis, we show the (nonGC) star-forming region Ser-emb-8.[18] The James Clerk Maxwell Telescope (JCMT) image has a spatial resolution of ∼10,000 AU, the CARMA image has a spatial resolution of ∼1000 AU, and the Atacama Large Millimeter/submillimeter Array (ALMA) image has a spatial resolution of ∼100 AU.

which further motivated the conclusion that turbulence dominates in this cloud. This kind of multiscale magnetic field analysis (in conjunction with MHD simulations) has not been conducted in the CMZ, even though the CMZ possesses a significant reservoir of dense molecular dust.

In addition to a multiscale analysis, the strength of the magnetic field can be estimated using the Davis–Chandrasekhar–Fermi (DCF) method.[19,20] The combination of a multiscale imaging analysis of the magnetic field morphology and studies of spectral lines probing turbulence will enable a comprehensive assessment of the dynamical importance of the magnetic field. Studying the geometry of the magnetic field has other important utility for deepening our understanding of the role of the magnetic field in the CMZ. The observations of the magnetic field can be compared with MHD models to determine the importance of turbulence in the CMZ clouds.[21,22]

Probe far-Infrared Mission for Astrophysics (PRIMA) observations will provide a key range of resolutions for a multiscale polarimetric analysis of star-forming regions in the GC. Furthermore, the PRIMA FIRESS spectrometer can be used in conjunction with imaging obtained from PRIMAger to enable an analysis of spectral lines tracing the turbulence within CMZ clouds. A good candidate line is the hydrogen deuteride line at 112 μm.[23,24] FIRESS will therefore be able to provide the information needed to estimate magnetic field strengths using DCF.

In this work, we detail possible future strategies for deepening our understanding of the CMZ magnetic field using the PRIMA observatory. In Sec. 2, we discuss the current state of our understanding regarding previous observations of the magnetic field in the CMZ. In Sec. 3, we present the exciting science potential of PRIMA that will enable even more powerful studies of CMZ magnetic fields. In Sec. 4, we discuss synergy between these aspirational observations and other current and next-generation instruments.

2 Previous CMZ Polarimetric Observations

The magnetic field toward the CMZ, as observed at far-infrared wavelengths, is complex. At arcminute resolutions (angular resolution of 1 to 2′, physical resolution of $\sim 10^6$ AU or 3.58 pc) using the PILOT and ACTpol surveys, the magnetic field is generally ordered and is largely parallel to the Galactic plane.[9,25] One possibility for this ordered, parallel field could be dust that is foreground to the central 150 pc of the Galaxy.[6] Higher-resolution observations at an angular resolution of ∼19.6″ (corresponding to a physical scale of $\sim 10^5$ AU or 0.78 pc) were recently obtained from the Stratospheric Observatory for Infrared Astrophysics (SOFIA) using the High-resolution Airborne Wideband Camera Plus (HAWC+) instrument at 214 μm.[6,26,27] The magnetic field obtained from these SOFIA/HAWC+ observations is shown in the upper panel of Fig. 3. The blue dashes show the magnetic field inferred from the 214 μm SOFIA/HAWC+ observations, with red and cyan dashes representing other submillimeter observations made using the Caltech Submillimeter Observatory (CSO)[30] and the James Clerk Maxwell Telescope (JCMT) SCUBA-2/POL-2[28,29] instrument, respectively. These observations show the magnetic field that threads the cool dust in the CMZ. The magnetic field revealed by these observations is more

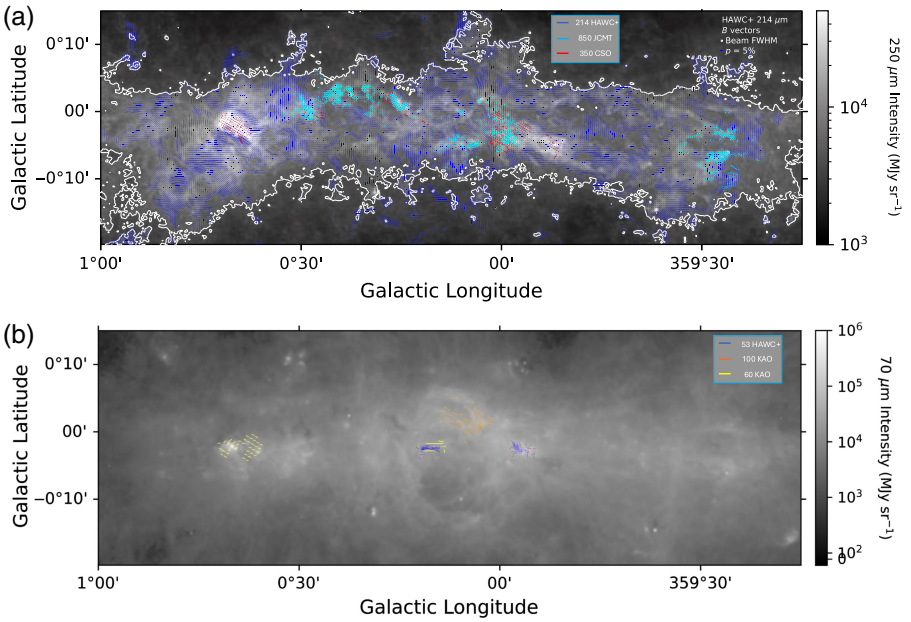


Fig. 3 Comparison of the magnetic field observed towards the CMZ for the cool (top) and warm (bottom) dust components, where the dust temperature ranges from 15 to 40 K.[7] (a) Magnetic field inferred from polarimetric measurements dominated by cool dust. The grayscale background is 250 μm Herschel emission of the CMZ.[7] Overlaid colored dashes indicate magnetic field orientations derived from SOFIA/HAWC+ 214 μm (blue), CSO 350 μm (red), and JCMT 850 μm (cyan).[6,28,29] (b) Magnetic field inferred from observations of warm dust. The grayscale background is 70 μm Herschel emission from the CMZ.[7] Overlaid colored dashes indicate magnetic field orientations derived from SOFIA/HAWC+ 53 μm (blue), and KAO 100 and 60 μm observations (yellow and orange).[28,30,31]

complicated than that inferred from PILOT and ACTpol with lower angular resolution, possibly indicating that FIREPLACE is largely probing the magnetic field local to the CMZ rather than some other foreground field component.[6]

In contrast to the magnetic field observed in the far-infrared, the magnetic field observed at radio wavelengths using instruments such as the Very Large Array (VLA) reveals a largely vertical (perpendicular to the Galactic plane) geometry.[32–34] It remains unclear how the radio and far-infrared magnetic fields connect. Although the SOFIA/HAWC+ observations have unveiled the magnetic field structure in the CMZ in most of the FIR bright cloud regions, there is considerable room for further improvement. In particular, the SOFIA/HAWC+ observations lack sensitivity to fields on scales larger than the 19.6″ (∼0.7 pc) beam size of SOFIA/HAWC+, meaning that the magnetic field distribution in fainter regions of the CMZ is not well determined.[6] PRIMA will enable an investigation of the large-scale fields that SOFIA/HAWC+ was not sensitive to. The extremely low background provided by PRIMA enables improved sensitivity to fainter CMZ structures. Investigating these fainter regions is important for probing how the magnetic field in the CMZ clouds connects to the vertical field system traced by the GC NTFs. Studying this connection will help determine how the seemingly distinct vertical and horizontal magnetic fields in the CMZ evolved. Studying such connections (or the lack thereof) can refine our understanding of the line-of-sight geometry of the thermal dust clouds and the NTFs. For example, if there are no connections between the magnetic fields traced by the NTFs and thermal dust, it could indicate that these structures are located at different points along the line-of-sight and are not interacting.

In addition, the improved sensitivity of PRIMA will enable the study of high-velocity gas located at the extreme edge of the CMZ. A recent study revealed extended cloud structures at high velocities (100 km s^{-1}) that could be a result of turbulent, shocked gas overshooting the CMZ after brushing by it.[35] These are faint, diffuse structures. meaning that the improved sensitivity and larger beam size of PRIMA compared with SOFIA/HAWC+ will be much better

suited to studying the polarization of these structures. This high velocity gas also connects to the bar and dust lanes of the Galaxy,[36] which the high velocity gas could be flowing along. PRIMA could therefore refine our understanding of these high-velocity structures by allowing us to probe the magnetic fields local to these clouds and how they compare to the higher density CMZ clouds. This understanding will be achieved by comparing how the polarization and magnetic field orientation varies in different cloud morphologies.[6] It will also be possible to compare how the magnetic field aligns with the molecular structure of the clouds using statistical methods such as the projected Rayleigh statistic,[37] which will make it possible to assess whether the conditions in these clouds parallel those observed in CMZ clouds or in Galactic disk clouds.[38,39] This understanding of high-velocity structures will make it possible to assess the impact of the magnetic field on the dynamics of the CMZ gas and connections between the CMZ and Galactic dust lanes.

PRIMA also extends to wavelengths down to ∼90 μm, which are crucial for two reasons. First, Herschel observations have revealed that warm dust in the Galactic Center (GC) has a morphology distinct from that of the cooler dust that dominates at longer wavelengths (see the lower panel of Fig. 3). Polarimetry at shorter wavelengths probes the field in regions where energetic events have heated the grains. The magnetic field geometry in these regions may provide insight into the role and response of the fields in such events. The magnetic field measurements at these locations provide a means to probe possible connections between the fields across a broad range of temperatures, column densities, and energy injection rates. The lower panel of Fig. 3 shows the 70 μm warm dust probed by Herschel with the existing polarimetric observations from ∼50 to 100 μm using the Kuiper Airborne Observatory (KAO). We do not currently have much insight into the magnetic field in regions containing warm dust despite the fact that it is a morphologically distinct dust population. Furthermore, there is currently no way to study the magnetic field of the warm dust at sub-arcminute resolutions.

Given the different dust populations, the sightlines in the GC are complicated. For example, Fig. 4 shows observations of the circumnuclear (CND) disk at 53 and 214 μm from SOFIA/HAWC+.[6,31] The CND is a cloud orbiting the central black hole of the Galaxy, Sgr A*, placing it at the heart of the CMZ.[41] The CND is an important reservoir of magnetized gas and dust that is likely facilitating accretion onto the Galactic black hole.[42,43] Furthermore, the magnetic field of the CND is strongly interacting with and being enhanced by the strong shear of the orbiting gas.[31,44] Furthermore, there is evidence that the polarization observed at different wavelengths for the CND is tracing different dust layers along the line of sight, such as a cool outer dust cloud and a warmer structure within the inner 5 pc of the GC.[45] The key to understanding such complex environments is multiwavelength total intensity and polarimetric observations. PRIMA uniquely

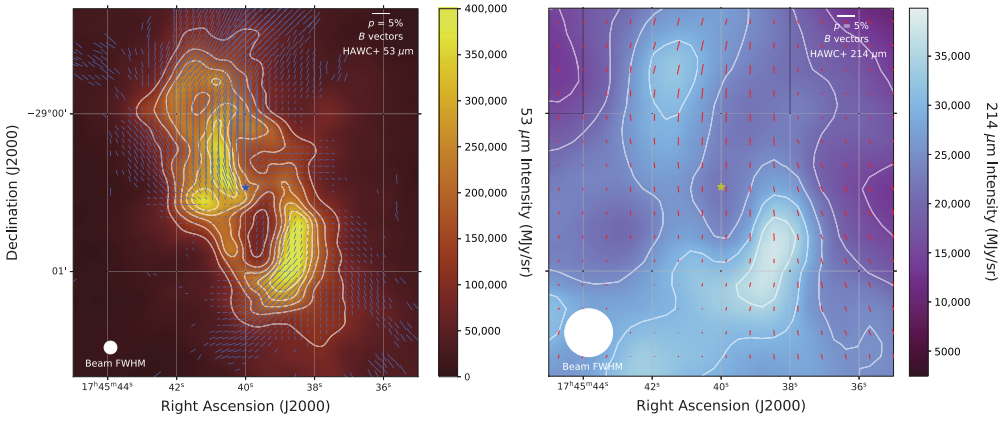


Fig. 4 The Galactic Center's circumnuclear ring has been observed by SOFIA/HAWC+ at 53 and 214 μm in both total intensity and polarization.[31,40] The morphology and magnetic field geometry differ significantly at the two wavelengths. This is likely due to the superposition of multiple cloud components along the line of sight with distinct temperatures and dust densities. Multiwavelength polarimetric imaging using PRIMA can be employed to elucidate this superposition, better understand the geometry of the dust, and untangle the interaction of the magnetic field with the strong shear of the CND.

covers the short wavelengths that are crucial for constraining the radiative and magnetic environments of the GC clouds.

3 Utility of PRIMA for Studies of the Galactic Center

A key method for assessing the importance of the magnetic field in a star-forming region is the study of how the magnetic field distribution varies over a range of spatial scales (such as in the example shown in Fig. 2). PRIMA will provide an important spatial scale for this kind of multiscale analysis, probing the molecular cloud scale ($\sim 10^5$ AU). Although this is the same scale probed by SOFIA/HAWC+, the higher sensitivity of the PRIMA observations will make it possible to conduct this analysis in fainter, more diffuse regions of the CMZ. The magnetic field derived from the PRIMA observations can then be compared with that derived from ALMA, which will have a much higher resolution sensitive to protostellar envelope spatial scales. For example, an ALMA proposal in cycle 11 to observe the largest molecular cloud in the CMZ was approved for time and will likely get observation time (proposal ID: 2024.1.00140.S, PI: Q. Zhang). This multiscale comparison is where a next-generation instrument with high sensitivity can enable a similar analysis without requiring an impractical amount of observation time.

PRIMA will be uniquely suited to furthering polarimetric studies of the magnetic field in the CMZ covering a range of wavelengths. Such studies will enhance our understanding of the impact of the magnetic field on the process of star formation, a fundamental process in astronomy. Furthermore, with the discontinuation of SOFIA, PRIMA will be the only far-infrared instrument capable of making key polarimetric measurements of the magnetic field in the warm dust in the CMZ. The warm dust appears to be a distinct component of the CMZ, as seen in Figs. 3 and 4. We note that as the FIREPLACE observations are largely observed to trace the CMZ clouds rather than some foreground component, the PRIMA observations of bright CMZ clouds will also be dominated by the CMZ emission. For fainter regions, there may be more significant contamination by other clouds along the line-of-sight. For these fainter regions, the potential impact of line-of-sight contamination will be assessed by studying the total and polarized intensity morphologies with the magnetic field orientations to assess whether they are tracing the same structure. If so, this indicates that the emission is dominated by the CMZ cloud contribution. If not, it would indicate that significant foreground contamination is occurring. This was the analysis employed by the FIREPLACE collaboration to quantify the extent of line-of-sight contamination in their SOFIA/HAWC+ observations.[6]

We describe a study that uses all four PRIMAger bands to observe the polarimetric distribution of the CMZ, as shown in Table 1. These bands will probe both the warm and cool dust populations. This data cube of maps can be considered spectral-polarimetric imaging, which probes the integrated signature of magnetized plasma and dust in the environment to differing depths of the molecular structures. By studying how the magnetic field varies over different temperatures, it is therefore possible to disentangle the effects of the magnetic field from

Table 1 Observational parameters for the PRIMA GC map.

Observation parameter	Values[a]
Map size	$\sim 1.5° \times 0.5°$
PRIMA instrument	PRIMAger
Wavelength used	96, 126, 172, and 235 μm
Beam FWHM	11, 15, 20, and 28″
Target total power sensitivity	386, 505, 425, and 475 MJy sr^{-1}
Target polarization sensitivity	3.86, 5.05, 4.25, and 4.75 MJy sr^{-1}
Time required to reach sensitivity	3.3, 1.1, 0.9, and 0.4 h

[a]PRIMA values are taken from Ref. 46 and Ciesla+2025, which is also part of this Jatis special issue.

changing temperature and density conditions. Furthermore, the PRIMA observations can be compared with observations obtained with other observatories to conduct a multiscale analysis of the magnetic field. Observations made by PRIMA can also be compared with MHD modeling of the large-scale CMZ field.[47] The angular resolution of the PRIMAger frequency bands will also be beneficial. The 28″ beam size of the 235 μm PRIMA observations can be compared with the similar 19.6″ SOFIA/HAWC+ observations. This point of comparison can be used to verify the accuracy of the PRIMA observations for high-intensity regions.

3.1 Description of Observations

To determine the time required for the PRIMA observations, we assume a 1 square degree field of view of the CMZ. We then require a 5σ detection of polarized emission of the CMZ assuming the CMZ clouds are 1% polarized and scaling the minimum Herschel intensities from 70 and 235 μm.[7] To perform the scaling, we assume $T = 41$ K, $\beta = 1.67$ for the 70 μm Herschel observations (warm dust component) and T = 22 K, $\beta = 1.67$ for the 250 μm Herschel observations (cool dust component). We scale only the cool dust component to estimate the sensitivity needed for the PRIMA 235 μm band estimate and scale only the warm dust component to estimate the sensitivity needed for the PRIMA 96 μm band. For the 126 and 172 μm band estimates, we take the average of the scaling of the warm and cool dust components at those frequencies. This scaling yields the total power sensitivities indicated in Table 1. The polarized intensity sensitivities are then obtained by choosing a conservative estimate that the clouds will have 1% polarization (generally, they are polarized at the few % level). Full polarimetric capability at the shortest wavelength band of PRIMA (96 μm) is critical to obtain polarimetric observations of the warm dust population. PRIMA is the only proposed next-generation instrument that is designed with full polarimetric capability over these wavelengths—a unique and valuable feature of this probe. The time required to observe the entire CMZ for all four PRIMA bands is shown in the bottom row of Table 1. This time is scaled from the 10 h surface brightness sensitivities shown on the PRIMA webpage[48] for a 1 square degree map.

4 Synergies with Other Observatories

The properties of the PRIMA observations would synergize with recent, existing, and forthcoming instruments. Table 2 lists key parameters of the PRIMA observations with current and anticipated capabilities of other instruments. The other instruments we compare are SOFIA/HAWC+,[40] PILOT,[49] ALMA,[50] the Large Millimeter Telescope (LMT),[51] the Fred Young Submillimeter Telescope (FYST),[52] and the JCMT (SCUBA-2/POL-2).[53] We note that Fig. 5 and Table 2 only list the 214 μm HAWC+ band. This is because only the 214 μm band observed the entirety of the CMZ in a manner comparable to the PRIMA observations. The observational parameters displayed for ALMA are using the upgraded ALMA2030 specifications.[54,55] In this table, we

Table 2 Comparison with other observatories (values are taken from the host organization websites, which are credited in the acknowledgments at the end of the article).

Observatory	Beam FWHM (″)	λ (μm)
PRIMA	11, 15, 20, and 28	96, 126, 172, and 235
SOFIA/HAWC+	19	214[a]
ALMA	0.005 to 31	315 to 8500
LMT	6 and 20	1100 and 3100
FYST	15, 32, 37, 47, and 59	350, 730, 850, 1000, and 1400
JCMT (SCUBA-2/POL-2)	9.6 and 14.1	450 and 850
PILOT	132	240

[a]Only the 214 μm SOFIA/HAWC+ band is shown because this is the only band that conducted a CMZ-wide polarimetric study.

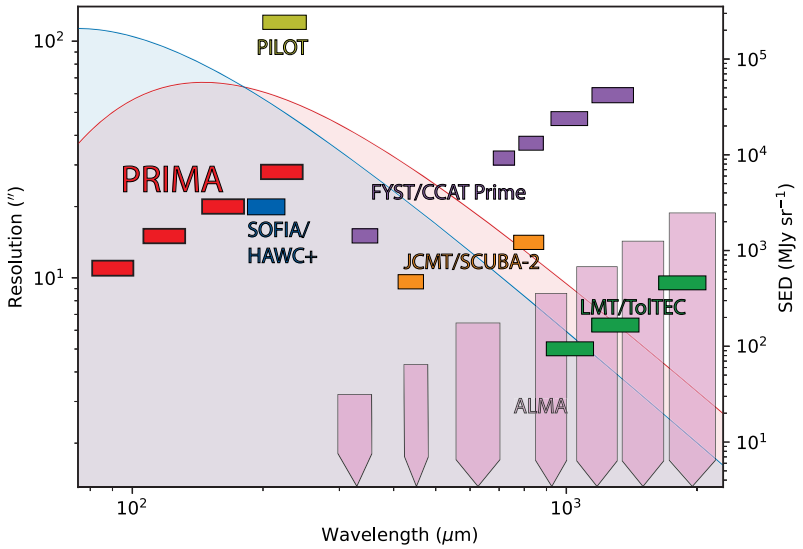


Fig. 5 Distribution of resolutions and spectral coverage from current and past far-infrared instruments, as listed in Table 2. Colored symbols indicate the capabilities of different instruments, as labeled. ALMA bands have a range of resolutions as indicated by the shape of the ALMA symbols (bands 4 to 10 are shown here). We only show the 214 SOFIA/HAWC+ band because this is the only frequency band that observed the entire CMZ. Greybody curves represent warmer and cooler representative dust SEDs for the GC (blue: $T = 41$ K, $\beta = 1.67$; red: $T = 22$ K, $\beta = 1.67$). The polarimetric coverage of PRIMA is uniquely positioned for understanding the warmer dust regions in the GC, which are heated by energetic events in the CMZ.

compare the resolutions and wavelengths that could possibly be used to observe the warm and cool dust in the CMZ. Other radio instruments, such as MeerKAT, that are not able to study the molecular cloud population are not included.

Figure 5 displays the different telescope resolutions and wavelengths graphically to visualize the unique wavelength and spatial range provided by the PRIMAger imaging bands. The PRIMA bands are shown as red boxes in the figure, and it is clear that PRIMA provides a unique window into the wavelength range of far-infrared emission.

For example, the observation specifications of PRIMA detailed here would synergize well with ALMA. As discussed previously, the arcsecond and sub-arcsecond resolution capabilities of ALMA would probe protostellar core and envelop spatial scales in the GC, whereas PRIMA is sensitive to molecular cloud scales. The behavior of the magnetic field can be compared at these different scales (in conjunction with MHD modeling) to assess whether the magnetic field or turbulence dominates in CMZ clouds. This CMZ PRIMA project would also synergize well with next-generation radio instruments such as the ngVLA and Square Kilometer Array (SKA). For example, the ngVLA and SKA will primarily operate at centimeter wavelengths, a wavelength range that will not be sensitive to the far-infrared dust emission. ngVLA observations can therefore be compared with the μm PRIMA observations to study connections between the CMZ clouds and the radio nonthermal structures observed in the GC. Similar work has previously been performed using VLA and SOFIA/HAWC+ observations,[38] but the combined analysis of PRIMA and ngVLA observations will represent a significant improvement in sensitivity to what is possible with current and recent observatories.

These PRIMA observations can also utilize the wide-field survey (WFS) that will be conducted using FYST.[56] The frequencies of the WFS survey (350, 730, 850, 1000, and 1400 μm) will complement the goal of studying how the polarization and magnetic field vary as a function of wavelength, enabling more extensive spectro-polarimetric analysis. The PRIMA frequency bands are a vital component of this analysis, making it possible to assess how the polarization and magnetic field vary between the cool and warm dust components in the CMZ, as described previously.

We can see from Table 2 that PRIMA provides unique and crucial capabilities in both resolution and frequency space. These capabilities will be invaluable for furthering our

understanding of the role of magnetic fields and the nature of dust in the CMZ. Work of this form will enhance our understanding of Galactic nuclear regions more generally.

Disclosures

The authors declare that there are no financial interests, commercial affiliations, or other potential conflicts of interest that have influenced the objectivity of this research or the writing of this paper.

Code and Data Availability

The data used to produce the figures shown in this paper are available on public data archives. The Herschel 250 and 70 μm observations shown in Figs. 1 and 3 are available on the NASA Infrared Science Archive. The SOFIA/HAWC+ observations shown in Figs. 3 and 4 are also on the NASA Infrared Science Archive. The data used to create Fig. 2 are available on SIMBAD, CDS, and the ALMA data archive. Observatory parameters listed in Tables 1 and 2 are taken from publicly available documentation on the observatory and operating organization websites.

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