Design Reference Mission Case Study
Stratospheric Observatory for Infrared Astronomy Science Steering Committee

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SOFIA Observations of The Circumnuclear Disk at the Galactic Center

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Scientific category:	INTERSTELLAR MEDIUM
Instruments:	EXES, FORCAST, FIFI-LS, GREAT, CASIMIR, HAWC
Hours of observation:	49

Abstract

The circumnuclear disk (CND) orbiting the supermassive black hole at the Galactic center at a distance of 1 to 5 parsecs holds the key for understanding the long-term activity of this unique and important region in our Galaxy. This torus of gas constitutes a reservoir of material that can fuel a violent episode of accretion activity (although it is not doing so at the present time) and might be responsible for the star formation evidenced by the cluster of massive stars occupying the central parsec. A few million solar luminosities of mid- and far-infrared radiation emerges from the CND, so it is ideally suited for study by several instruments on SOFIA. Here, we propose a comprehensive investigation aimed at refining our understanding of the physical state and the structure of the CND. The results will inform a new generation of models that are sufficiently elaborated to confidently project the past and future evolution of this disk.

Observing Summary:

Target	RA	Dec	$F_{\rm Jy}$	Configuration/mode
.5 CND	17 45 40.041	-29 00 28.12	$>$ 0.25 Jy arcsec^{-2}	24.4 μm FORCAST IMAG
.5 ”	”	”	$>$ 0.25 Jy arcsec^{-2}	32 μm FORCAST IMAGIN
.5 ”	”	”	$>$ 0.25 Jy arcsec^{-2}	38.4 μm FORCAST IMAG
.0 CND	”	”	$>$ 0.05 Jy arcsec^{-2}	53 μm HAWC IMAGING:
.75 ”	”	”	$>$ 0.03 Jy arcsec^{-2}	88 μm HAWC IMAGING:
.25 ”	”	”	$>$ 0.01 Jy arcsec^{-2}	155 μm HAWC IMAGING:
.1 ”	”	”	$>$ 0.003 Jy arcsec^{-2}	215 μm HAWC IMAGING:
.8 CND	”	”		18.7 μm EXES, HIGH-RES
.4 ”	”	”		25.2 μm EXES, HIGH-RES
.8 ”	”	”		25.9 μm EXES, HIGH-RES
CND	”	”		52, 63, 88 μm, simultaneou
.5 CND	”	”		CO lines from 96-186 μm F
CND	”	”		63 μm GREAT
CND	”	”		7 molecular lines CASIMIR
CND	”	”	$>$ 0.003 Jy arcsec^{-2}	53, 88, 155, 215 μm HAWC
				Grand total hours

NOTE: This grand total (44) does not equal the number (49) given on page 1

Scientific Objectives

The circumnuclear disk of our Galaxy (the CND) was discovered with the Kuiper Airborne Observatory (Becklin, Gatley & Werner 1982), and has been extensively studied since, both as an airborne target (e.g., Davidson et al. 1992; Chan et al. 1997; Latvakoski et al. 1999) and as a source of copious millimeter-wave molecular line emission (Güsten et al. 1987; Marr et al. 1993; Wright et al. 2001; Christopher et al. 2005). It consists of a ring, or a torus, with an inner radius of 1 parsec and a radial extent of several parsecs (figures 1 and 2). The mostly molecular CND connects the gravitational domain of the central supermassive black hole (radii < 1.5 pc) to that of the centrally concentrated nuclear bulge of stars. The rotation of the CND is indicative of a well-ordered Keplerian velocity field in the inner parts (Jackson et al. 1993), so the CND has been in place for $\gg 10^4$ years. Circumnuclear disks have been abundantly found in the nuclei of spiral galaxies, and they are widely deemed important for being agents of mass accretion onto the supermassive black holes around which they orbit (e.g., Ferrarese & Ford 1999; Herrnstein et al. 2005). The scale of the Galactic CND places it at the smaller end of the range of known disks, but because of its proximity, we can explore it in far greater detail than is possible elsewhere, and we can consequently use the CND to investigate the process of mass accretion into a galactic center and onto a supermassive black hole.

The CND of our Galaxy is an unusually high-excitation source, heated approximately equally by the central stellar cluster of old stars and by the UV flux from the bright young stars clustered around the black hole (Davidson et al. 1992; Telesco et al. 1996). The gas temperature within the molecular and atomic medium is several hundred K (Lugten et al. 1987), and the densest clumps in the disk may have densities as high as 10^8 cm^{-3} (Christopher et al. 2005). The total ultraviolet luminosity inferred to arise from within the CND is $\sim 10^7$ L$_\odot$. This internal heating source gives rise to a decreasing temperature gradient outwards from the hot, ionized inner edge of the disk (Sutton et al. 1990; Bradford et al. 2005). However, the poorly characterized clumping of the CND is an important determinant of how well the UV radiation can penetrate into the CND from its interior.

More prominent than the CND itself in many observable diagnostics is the central HII region, Sagittarius A West, also known as the "mini-spiral" – a group of gas streams lying within the inner cavity of the CND (Paumard et al. 2004), and including the ionized inner edge of the CND itself (Roberts & Goss 1993; Morris & Serabyn 1996). Not all of the gas within the CND is ionized; the KAO was used to infer the presence of warm atomic gas, in which case the ionized gas streams presumably lie at their surfaces (Jackson et al. 1993; Davidson et al. 1992). The total mass of these features is small ($\sim 10^2$ - 10^3 M$_\odot$), compared to the mass of the CND (10^4 - 10^5 M$_\odot$), but these streams apparently represent an accretion flow onto the central black hole, so they are believed to play a key role in producing some of the activity there. The streams of the mini-spiral are likely to have originated from the CND, either as a result of instabilities at the inside edge of the disk, or as a result of collisions of clouds with portions of the CND (Morris & Serabyn 1996, and references therein).

SOFIA's unprecedented angular resolution 8.5" *(λ/100 μm) FWHM for $\lambda > 15$ μm will allow us to examine details of the morphology of the CND and minispiral structure on scales comparable to their major elements, ∼10", at wavelengths $\lesssim$ 100 μm. Numerous open questions about the CND that are crucial to our understanding of this structure can therefore be well addressed:

1. **What is the source of matter that supplies this gas reservoir?** The possibilities include a) the CND has been produced by an infalling cloud which has created a dispersion ring as it has become tidally stretched and self-intersecting (Sanders 1998), and b) the CND has resulted from a steady build-up, including the quasi-steady-state accumulation of gas resulting from mass loss from bulge stars and from inwardly migrating gas in the Galactic disk (Vollmer & Duschl 2002). An answer to this question can be informed by mapping the CND in the dust continuum, and in particular, by elucidating the structure of its outer boundary.

2. **Has the CND been affected by the passage of the shock associated with the supernova remnant, Sgr A East?** The CND and the contents of its interior cavity are projected to lie within the shell of this prominent supernova remnant, seen in nonthermal radio emission and in X-rays (Yusef-Zadeh & Morris 1987; Pedlar et al. 1989; Maeda et al. 2002; Park et al. 2005). Cool gas snowplowed up by the expanding shell itself is seen in millimeter continuum and molecular line observations (Mezger et al. 1996, and references therein). Sgr A East is presumably quite close to the CND (Herrnstein & Ho 2005), so passage of the supernova shock over the CND may have occurred quite recently (Maeda et al. 2002; Rockefeller et al. 2005). The distorted morphology of the exterior portions of the CND can perhaps be ascribed to the effects of this blast wave. A better characterization of the dust distribution in the outer parts of the CND will facilitate an assessment of this possibility.

3. **What is the temperature structure of dust in the CND, and what is its spectrum of density fluctuations?** These questions will be informed by multi-wavelength observations from 10 to 200 μm. Modelling the temperature and density structure will allow us to infer, or at least constrain, the clump size distribution, the volume filling fraction of clumps, and the opacity of the clumps. These functions and parameters play an important role in the determination of the total mass of the CND (Christopher et al. 2005), the tidal stability of its clumps (Vollmer & Duschl 2001a, b), and the depth of penetration of luminous energy arising in the interior cavity.

Questions 1-3 can all be addressed using both FORCAST and HAWC for sensitive, full-resolution mapping of the CND out to where it merges with the general background emission from the region. The mapping will be carried out by FORCAST (24.4, 32, and 38.4 μm) and HAWC (53, 88, 155, and 215 μm), in order to provide observational tests of models of dust heating by a central source, in which the radiation diffuses outward through a chosen distribution of opaque clumps. The models will incorporate a detailed specification of dust emissivity, so that the grain size distribution plays a role, as well as grain composition, so that grain composition is accounted for (*e.g.*, the broad 30 μm feature attributable to MgS (Chan et al. 1997)).

4. **How much material is present in the interior of the CND, and what is the relationship of this material to the CND?** That is, have the gas streams present in the central cavity been pulled out of the CND by some instability at the interior interface, or by angular momentum loss as a result of some cloud collision? The KAO was instrumental in revealing the presence of material inside the ring, and SOFIA can take that study to the next step by mapping its distribution with much better spatial resolution. The ionized mass can be determined using the ratio of the [O III] 52 and 88 μm lines, which give a measure of the electron density, n_e. (So also do the [N II] lines at 122 and 205 μm for lower density regimes, though with reduced angular resolution.) Comparing this n_e with the emission measure n_e^2L from radio observations, one obtains a measure of the depth L of the ionized gas, and thus the column density and mass.

The mass of neutral atomic gas in the cavity interior to the CND appears to be an order of magnitude larger than that of ionized gas. From KAO measurements of the [O I] 63 μm line with 22" angular resolution and ~30 km s^{-1} spectral resolution, Jackson et al. (1993) infer a neutral (H) mass of ~300 $M_\odot$ and an infall rate of ~0.03 $M_\odot$ yr^{-1}, within 1 pc of SgrA*. The 145 μm line of [O I] can help to establish optical depth of the 63 μm line, which is important for doing this analysis thoroughly. The higher angular and spectral resolution measurements of this neutral gas flow field which are made possible with SOFIA can be used to determine in detail its relation to the ionized cavity gas and to the CND, and to estimate more accurately the neutral gas mass. To examine in finer detail the correlation of the neutral and ionized gas velocity fields claimed by Jackson *et al.*, we propose observations at ~15 km s^{-1} resolution to compare with the Brackett-γ maps of Paumard et al. (2004, 0.5" spatial and 21 km s^{-1} spectral resolution) and with the radio H92α map of Roberts & Goss (1993, 2" spatial and 14 km s^{-1} spectral resolution).

The determination of whether the OI-emission is produced in shocks or in photodissociation regions (PDRs) can be made using the SI 25.2 μm line, which is produced in shocks but not in PDRs. Submillimeter rotational water lines can also provide information on shock structures, although with reduced spatial resolution. It will be important to image the [C II] 158 μm line even though the angular resolution will be ~14", because its emission is the major PDR gas coolant.

5. **What are the physical conditions in the CND, and are clumps in the medium stable to tidal disruption and to gravitational collapse to form stars?** Observations of HCN and HCO^+ in the CND with ~5"x3" resolution by Christopher et al. (2003) reveal 26 maxima of mean size ~7", interpreted as dense (~3 x 10^7 cm^{-3}) cores having masses ~3 x 10^4 $M_\odot$, both of which are high enough to allow for star formation. However, these masses are estimated indirectly using virial theorem arguments. Given the high temperatures and column densities in such cores, we propose to observe the 17 and 28 μm electric quadrupole lines of molecular hydrogen there to obtain a *direct* measure of their molecular mass. Al-

though the column densities in the cores are adequate to produce detectable emission, the gas and dust in the cores are likely in thermal equilibrium, so the line-to-continuum ratio depends on the line and continuum opacities and it may be small if both opacities are large.

We can anticipate high-J CO emission originating in the ~50 K molecular gas of the CND (*e.g.*, J = 14-13 at 186 μm, corresponding to T~75 K). These CO lines will be optically thinner than the longer wavelength J=1-0 and 2-1 lines measured at mm wavelengths, and presumably provide most of the gas cooling from the CND. Linewidths will be about equal to those of HCN, namely 26 km $^{-1}$. The distribution of their relative intensities and line-widths will help to unravel details of the CND heating. The inevitable beam dilution for the longer wavelengths caused by telescope diffraction means that lines with wavelengths $\lesssim$ 200 μm will provide the most useful diagnostics of the CND. The high-J lines of the higher dipole moment molecules HCN and HCO^+ will also be employed to investigate the CND, because they will be most useful for determining the distribution of gas densities in the region. Ground-based interferometric observations of the low-J transitions of these molecules will complement the SOFIA observations by providing important high-resolution information about the spatial distribution of the molecules.

6. **What role does the circumnuclear disk play in affecting the activity of the central parsec?** The CND represents a substantial reservoir of gas that can possibly be accreted onto the central black hole at a much higher rate than at present, so it can lead to energetic accretion events that have a strong impact on the immediate and long-term evolution of the central parsec. Careful measurements of the velocity fields in the inner portions of the CND, and in the gas streams apparently peeling off of the CND, using the heterodyne instruments on SOFIA and the spectral lines described in item #5, will constrain and perhaps inspire models of the radial inflow of gas and its causations.

7. **Can the ionization of the gas of the mini-spiral and the surrounding low-density cavity inside the CND be explained completely by photoionization from stars in the central cluster?** If so, then we can rule out a significant role for either energetic shocks or ionization by X-rays or high-energy particles. Relative intensities of [O III] (52 μm) and [S III] (18.7 μm) provide a measure of the gas excitation. Imaging these lines over the cavity will reveal possible gradients in the excitation, related to the location of the ionizing sources. The variable extinction over the region is well known (Scoville et al. 2003), and can be accurately accounted for, especially since extinction is not large for these mid- and far infrared lines. Much of the excitation is thought to be produced by stars with $T_{eff} \lesssim$ 35,000 K (Lacy et al. 1991). However in a ~14x27" beam, Lutz et al. (1996) measured emission from [OIV] 25.9 μm from ISO. This excitation is too high for production by late O stars. With SOFIA, we can image this line with ~3" angular resolution, to seek the origin(s) of its excitation, possibly WR stars.

Questions 4-7 will be investigated using SOFIA's arsenal of first-generation spectrometers: EXES, FIFI-LS, GREAT and CASIMIR.

8. **What is the detailed magnetic field geometry of the CND, and with the spatial resolution available to SOFIA at far-IR wavelengths, can fluctuations in the magnetic field direction be measured?** Measurements of such fluctuations would be important for understanding the interplay between turbulence and the magnetic field, and thus for determining the direction and strength of the magnetic field.

9. **To what extent does the magnetic field affect the dynamics of the disk?** Can the turbulent motions be described entirely as MHD turbulence, i.e., as magnetosonic and Alfvénic waves? High-resolution measurements of the direction of the magnetic field throughout the disk using a far-infrared polarimeter will enable sufficiently detailed models for this question to be addressed, such as an elaborated version of the model of Wardle & Königl (1990).

10. **Is there any evidence that the toroidal magnetic field in the CND links up to the exterior field, believed by many to be dipolar?** There are indications of this from KAO studies of the CND (Hildebrand et al. 1993; see also Novak et al. 2000), but confirmation will require measurements with higher spatial resolution over a greater area.

Questions 8-10 can be addressed by adding a polarimetric capability to the HAWC array, giving a spatial resolution 5 times better than was possible with the KAO.

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SOFIA Uniqueness/Relationship to Other Facilities

For the research described here, it is essential to utilize the highest possible spatial resolution in the far-infrared. This means using either an airborne or an orbital platform. The MIPS camera on the Spitzer Space Telescope does not have adequate spatial resolution to improve significantly on past results from the KAO, and, in any case, the Galactic center is too bright to use MIPS without imprinting the array with long-lasting persistence images that render the data unusable. No other existing or planned observatory can carry out the far-infrared continuum observations described here.

The proposed spectroscopic observations of the CND are best done with SOFIA because this is such a high-excitation source. While millimeter and submillimeter molecular lines that can be observed from ground-based observatories provide essential information for modelling the CND, the highest density and highest temperature portions of the medium are best

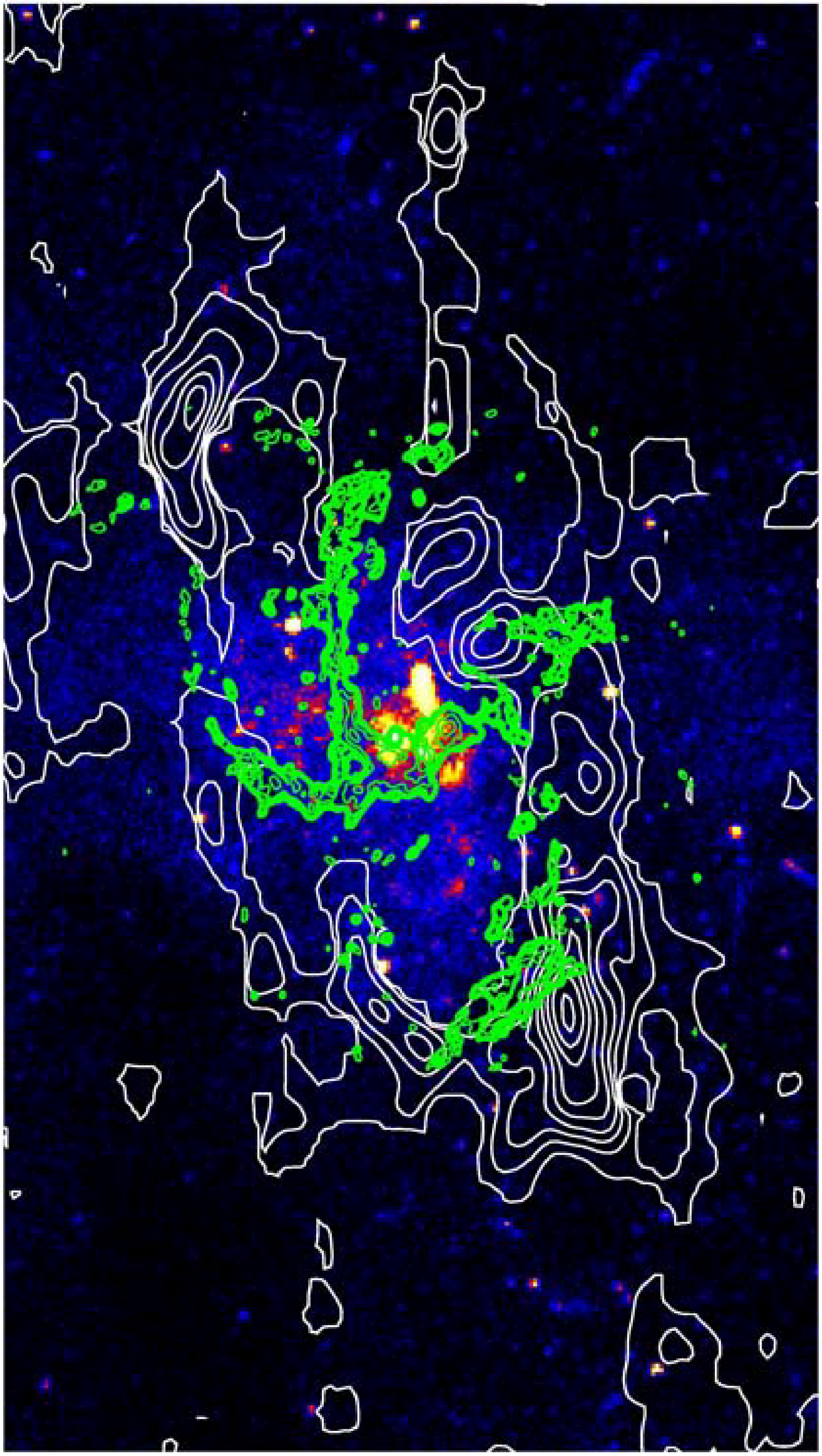

Figure 1: The Circumnuclear Disk, as seen in HCN emission (white contours, from Christopher et al. 2005). Green contours represent $\lambda 6$ cm radio continuum emission from the VLA, and the underlying false color background represents 2-8 keV X-ray intensity, which is brightest inside the inner cavity of the CND (Baganoff et al. 2003). The physical scale of the region shown is 4 pc x 2 pc.

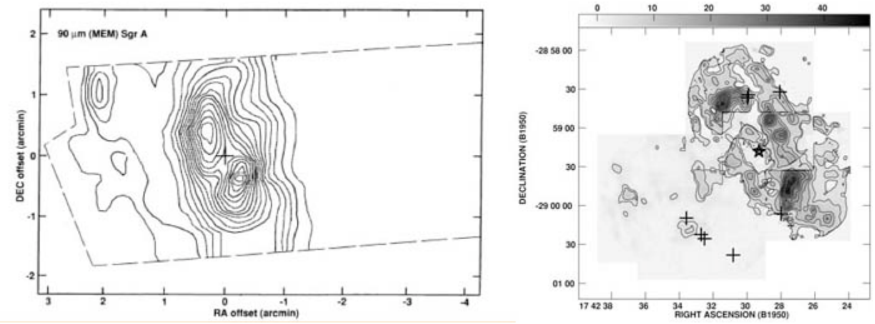

Figure 2: left: The Circumnuclear Disk measured at 90 μm with the Kuiper Airborne Observatory (Davidson et al. 1992). right: molecular hydrogen emission measured in the CND with the Hubble Space Telescope (Yusef-Zadeh et al. 2001). The crosses represent the locations of 1720-MHz OH masers.

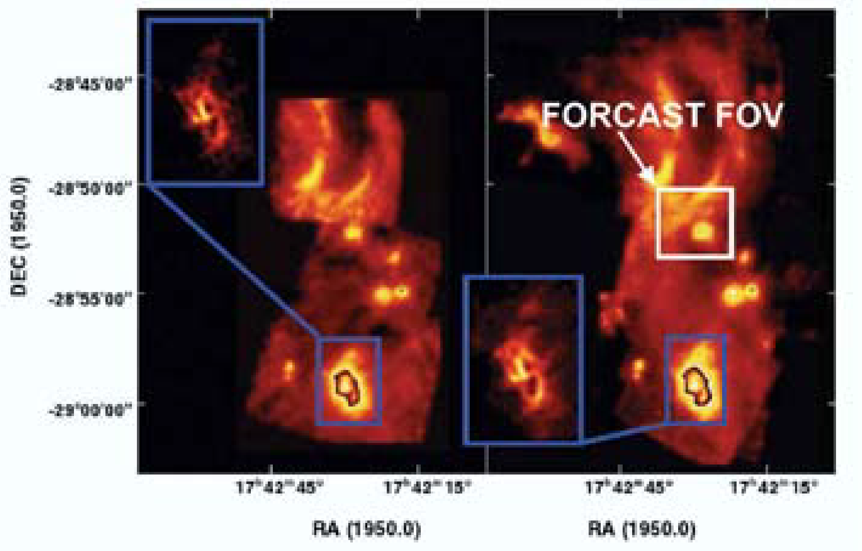

Figure 3: The 3.2 x 3.2 arcminute field of view of FORCAST superimposed on the KWIC map made on the KAO by Latvakoski et al. (1999). The left image was taken at a wavelength of 31.5 μm and the right image at 37.7 μm. The insets show details of the CND and SgrA West in its interior.

probed with the high-lying lines emitting in the frequency range well above 500 GHz, the range accessible to CASIMIR and GREAT. Even ALMA, when eventually finished, will not be able to observe in the important high-frequency range. Furthermore, the atomic fine-structure lines, which are important for investigating the photochemistry of the medium, are not accessible with any existing or planned ground-based platform, but are well suited for observations with EXES and FIFI-LS on SOFIA. Herschel, when it flies, will be able to carry out some of the spectroscopy described here, but observing time on Herschel is extremely limited, and its spatial resolution will be poorer than that of SOFIA. Some of the mid-IR fine structure lines discussed here are accessible with IRS on Spitzer, but with extremely limited velocity information, and with subtantially poorer spatial resolution than with SOFIA.

Observing Strategy

The FORCAST observations addressing questions 1-3 will be carried out at 24.4, 32, and 38.4 μm. A single field of view (3.2' x 3.2' or 8 x 8 pc) is large enough to include the entire CND (see figure 3). While 15 minutes on source is sufficient to achieve a sensitivity >20 times greater than was obtained by Latvakoski et al. (1999), the proposed time of 1.5 hours per filter includes time for setup, nodding and calibration, and is conservative because we anticipate that multiple reference positions will be needed to ensure a clean sky reference, and because the image will be dithered by a small amount during the observation.
The proposed HAWC observations are designed to cover a 4' x 3' region, so require 24 pointings at 53 μm, 12 pointings at 88 μm, 4 pointings at 155 μm, and 2 pointings at 215 μm. These fields will all have ~25% overlap. The speed of the observations is determined not by sensitivity, but by the nodding strategy in this complex region. The proposed observations can be accomplished in 3.1 hours.
The line observations to address questions 4-7 consist of the following, with the required velocity resolutions indicated:
EXES: [S III] 18.7 μm, [S I] 25.2 μm, [O IV] 25.9 μm; R~20,000 (15 km/s)

FIFI-LS: [O III] 52, 88 μm, [O I] 63 μm, R~3000 (100 km/s)
[O I] 145 μm, [C II] 158 μm, CO J=14-13, 17-16, 22-21, 27-26 ; R~2000
GREAT: [O I] 63 μm; R~20,000 (15 km/s)
CASIMIR: CO 8-7, 10-9, 12-11, HCN 6-5, 8-7, 9-8, 12-11, 13-12, HCO^+ 11-10 (5 km/s)

The selected molecular lines are all in atmospheric windows. The spectral line observations with FIFI-LS would be paired to take advantage of being able to observe two lines simultaneously in first and second order. We would use the lower spectral resolution map of FIFI to plan the GREAT observations of the dynamics of the neutral oxygen at ~15 km/s resolution. These observations will require a few hours on Sgr A West per instrument, including set up and observing overhead. For EXES and FIFI-LS, there is overhead to remove systematic effects from extended emission because of the need for chopping. Calibration will take another hour on a different observing leg. For example, in 5 hours, GREAT could nyquist sample nearly an entire 100" x 100" area around the CND with S/N~10 at flux levels ∼10% of the peak value.

The proposed polarimetric observations with a second-generation polarimeter (presumably an elaboration of HAWC) assume the same pointings as are proposed for the HAWC continuum intensity observations. The time estimate assumes a polarimetric S/N ratio of 3, which gives ±10° on the polarization angle for measurements of the minimum flux. Taking the minimum flux at 50 μm from Becklin, Gatley & Werner (1982) to be 0.5 Jy arcsec^{-2}, and assuming 1% polarization, we calculate a total required integration time of 28 hours for the single HAWC array. [This would be reduced to 14 with a polarimeter employing dual arrays.]

Special Requirements

RMS pointing jitter: 2.0 as

Precursor/Supporting Observations

Interferometric molecular line data on the Galactic circumnuclear disk will be gathered, first by the CARMA array during the same time period as the initial SOFIA observations, and then by ALMA a few years later. These data will be invaluable complements to spectral line data taken with SOFIA in two ways: first, they will extend the range of energy levels for molecules having lines in the millimeter range, and thereby allow for an improved model of the excitation. Second, the high spatial resolution of the interferometers will guide the interpretation of the spatial distribution of line emission measured with SOFIA, by providing some information about the clumping or density stratification of the medium.

Related SOFIA Investigations of the Galactic Center

The circumnuclear disk is one of many important projects that can be carried out in the Galactic center with SOFIA. Other top priority projects might include:

1. *A study of the interaction of massive, young star clusters, such as the Arches and Quintuplet clusters, with their interstellar environments.* Such interactions include heating of nearby dust, the ionization of nearby gas, and the effect of strong shocks as stellar winds impact nearby clouds. The energy flow from cluster stars to the interstellar medium has profoundly important consequences for the evolution of the interstellar medium in the unique environment of the Galaxy's central molecular zone, and SOFIA is uniquely suited to investigate this energy flow.

2. *An investigation of the mystery of star formation in the Galactic center.* Because the conditions for star formation are so different near the Galactic center, compared to elsewhere in the Galaxy, stars may form more often there in massive clusters and they may have a top-heavy initial mass function. Understanding this is important for understanding activity in Galactic nuclei in general, and SOFIA can be used to illuminate these issues through observations of the environments in which star formation is currently taking place.

3. *The extreme case: the blast of star formation in our Galaxy's supercloud, Sagittarius B2.* Sagittarius B2, arguably the most massive molecular cloud in our Galaxy, is currently forming stars at an enormous rate. SOFIA offers an unprecedented ability to study this monstrous cloud, and the activity within it.

4. *Exploration of the chemistry of the warm, dense, turbulent reservoir of gas in the Central Molecular Zone.* With almost 10^8 $M_\odot$ of gas in the central few hundred parsecs of the Galaxy, the CMZ represents a rich arena for studying interstellar chemistry. SOFIA's complement of spectroscopic instruments is uniquely suited for studying molecules at much higher frequencies than can be employed from ground-based observatories, providing insights to the chemistry of lighter molecules (notably hydrides) and the role of atomic constituents.

5. *Characterization of very-large-scale shocks.* Galactic-scale shocks occur in the CMZ because of the Galaxy's pronounced bar potential. In addition, some have argued that major explosive events taking place at or near the Galactic nucleus have given rise to extremely powerful shocks propagating out of the Galactic center. Such shocks give rise to emission from dust and gas that can be studied in detail by most of the instruments on SOFIA. A full characterization of such shocks would allow us to understand their dynamical origins.

6. *A study of magnetically organized dust structures.* The MSX and Spitzer satellite observatories have revealed the presence of a number of large-scale dust emission features that appear to have been geometrically organized by the known, strong magnetic field in the Galactic center. SOFIA can advance our understanding of these key structures by providing spectroscopic information and by providing detail on fine-scale morphological structures unresolved by previous observations.