SOFIA Quick Guide

Instrument Capabilities & Science Cases

SOFIA

Stratospheric Observatory for Infrared Astronomy

SOFIA Quick Guide

Instrument Capabilities & Science Cases

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Further Information

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SOFIA Help Desk

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December 2021

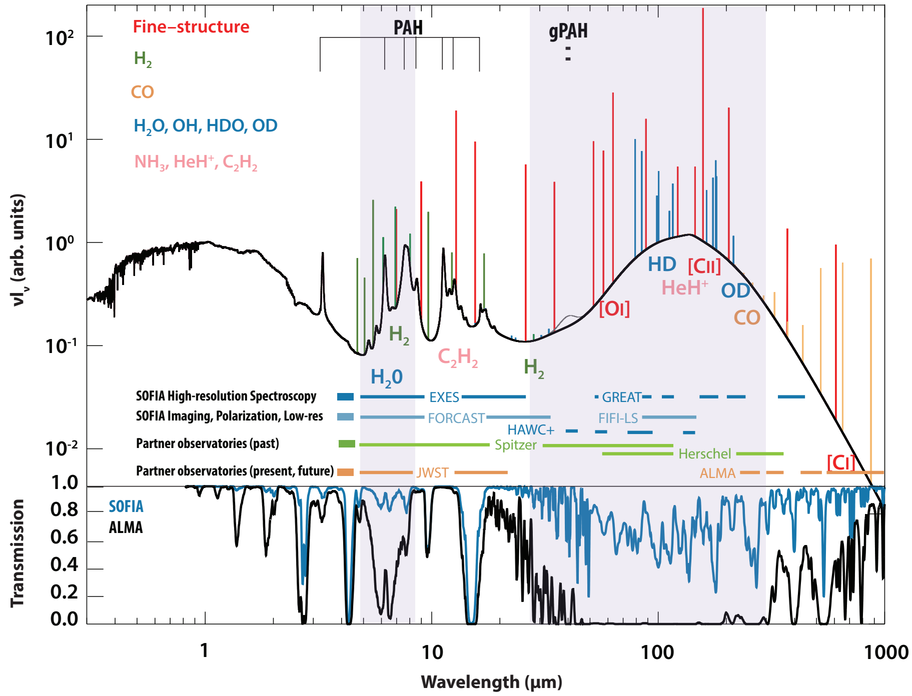
Front cover image based on "Surveying the Giant H II Regions of the Milky Way with SOFIA. I. W51A," Lim et al., 2019.
(NASA/SOFIA/James De Buizer, Wanggi Lim; NASA/JPL-Caltech)

Back cover image based on "HAWC+/SOFIA Multiwavelength Polarimetric Observations of OMC-1," Chuss, David T., et al., 2019.
(NASA/SOFIA/D. Chuss et al. and European Southern Observatory/M.McCaughrean et al.)

Infrared Astronomy and the SOFIA Observatory

Infrared Astronomy

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is an airborne observatory operating at altitudes of 35,000–45,000 ft, above 99% of the Earth's atmospheric water vapor. Infrared observations allow for the direct measurement of the physical properties of ionized gas (T ~ 104 K), neutral atomic gas, and warm (T ~ 100-500K) molecular gas without obstruction by dust attenuation as with traditional UV and optical diagnostics. In particular, more than half of all the light emitted from stars is absorbed by dust and re-emitted in the infrared.

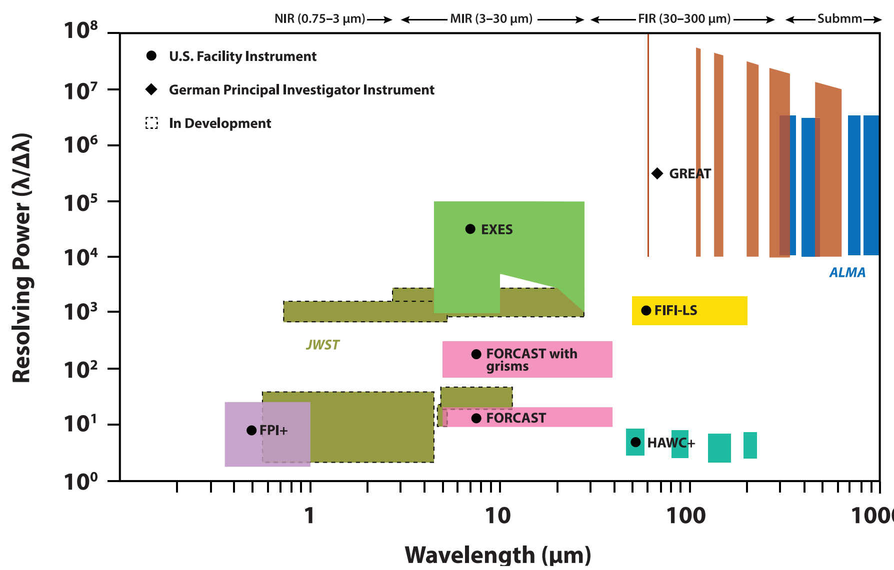


Atmospheric transmission of SOFIA and astronomical lines of interest on a model spectral energy distribution of a photodissociation (PDR) region. *(Ennico et al.)*

The SOFIA Observatory

A suite of instruments with coverages ranging from 0.36–612 μm are available for imaging, spectroscopic, and polarimetric observations. Together, the SOFIA instruments bridge the gap between the radio telescope Atacama Large Millimeter Array (ALMA; 300–9600 μm) and the James Webb Space Telescope (JWST; 0.6–28 μm) to be launched in 2021. This Quick Guide provides the technical specifications for each available instrument, along with examples of astronomical observations obtained with each.

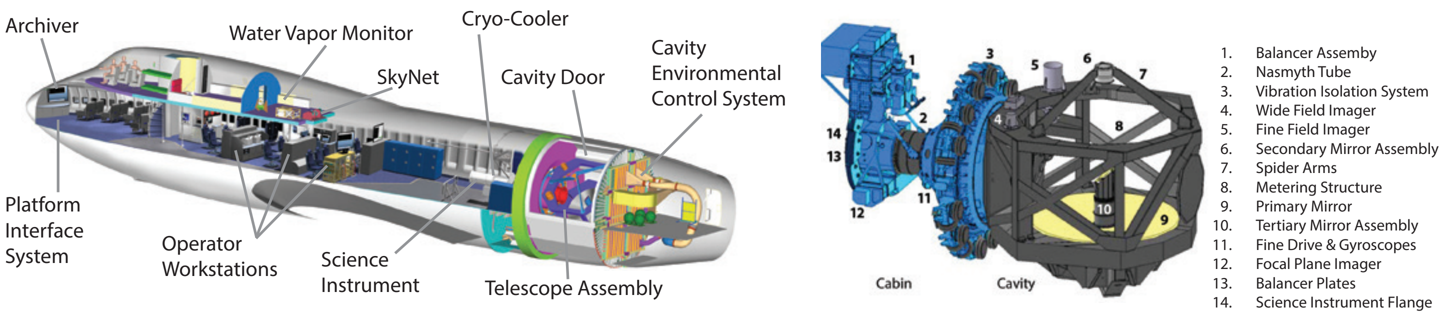
The SOFIA Instruments



Telescope and Image Quality

The SOFIA Telescope

Mounted onboard an extensively modified Boeing 747SP aircraft, the 2.5m class Cassegrain telescope with Nasmyth focus is the largest telescope ever integrated into an aircraft. It provides an unvignetted field-of-view (FOV) of 8 arcmin to the science instruments. A 45° gold coated dichroic mirror allows transmission of optical wavelengths that are redirected to a visible Nasmyth focus where it feeds the Focal Plane Imager (FPI), with an 8' circular FOV. Two other guiding cameras are attached to the front ring of the telescope and provide guide fields of 6° x 6° and 67' x 67' FOV, respectively.



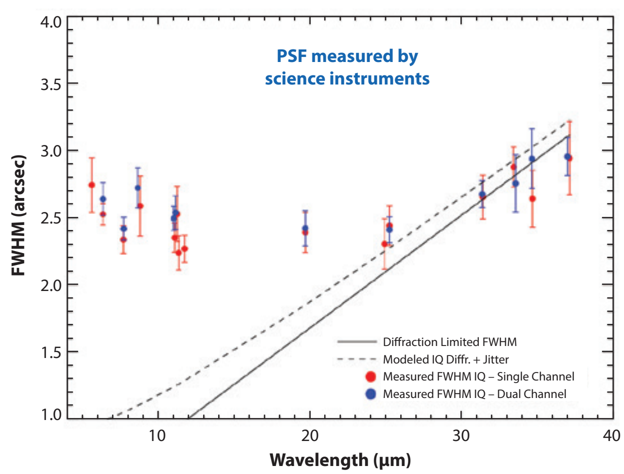
Schematics of the SOFIA aircraft *(left)* and telescope *(right)*. (*Reinacher et al.)*

Image Quality

The telescope is subject to both the stratospheric environment — pressures of 0.2 bar and temperatures of −40°C — and the aircraft's vibrations and motions. It is inertially stabilized by electronic fiber optic gyroscopes and feedback from the FPI, moved by magnetic torquers around a 1.2m diameter spherical pressurized oil bearing.

The diffraction limit of a telescope defines its maximum achievable resolution, and the Point Spread Function (PSF) delivered by SOFIA is highly wavelength dependent. For wavelengths longer than ~30 µm, the system is diffraction limited. For shorter wavelengths, the PSF is dominated by a combination of diffraction, jitter, optical aberrations, and defocus. Other factors that degrade image quality include turbulence and cavity seeing.

Pointing accuracy astrometry software is used to identify the stars in the field of the Focal Plane Imager (FPI+), then determine the position of the instrument boresight pixel on the FPI+. Image stability is maintained by the Flexible Body Compensation system, which uses high-sampled accelerometer measurements to estimate the jitter and compensate it at frequencies of up to 50 Hz. The uncertainty in the astrometric position is about 0.2 arcseconds.



Representative FWHM PSF in select filters as measured during Cycle 7. Also shown are the diffraction limited FWHM (solid line; calculated for a 2.5-m primary with a 14% central obstruction) and the modeled IQ (dashed line), which includes shear layer seeing and 0.5 arcsec rms telescope jitter (corresponding to 0.83" FWHM).

System Characteristics and Science Instruments

System Characteristics

Nominal Operational Wavelength Range	0.3 to 1600 μm	Maximum Chop Throw on Sky**	± 4 arcmin
Primary Mirror Diameter	2.7 meters	Image Quality of Observatory System	Diffraction-limited at λ ≥ 30 μm (corresponds to 2.7 arcsec FWHM at 30 μm)
Effective Aperture Diameter	2.5 meters	Chopper Frequencies	1 to 20 Hz for 2-point square-wave chop
Optical Configuration	Bent Cassegrain with chopping secondary mirror and flat folding tertiary	Pointing Stability	≤0.4 arcsec (radial rms) for sidereal targets ≤1.0 arcsec (radial rms) for non-sideral targets
System f-ratio	19.6	Pointing Accuracy	0.3 arcsec (radial rms) with on-axis focal plane tracking
Primary Mirror f-ratio	1.28	Total Telescope Emissivity*	≤14.5% over 8.45–8.75 μm bandpass with dichroic tertiary
Telescope Elevation Range**	23 to 57 degrees (approx.)	Observatory System Polarization	≤1.8% across 40–300 μm
Field-of-View Diameter**	8 arcmin	Recovery Air Temperature in Cavity (Optics Temperature)	240 K

* Estimated value ** Unvignetted

Science Instruments

Name	Principal Investigator	Description	Wavelength Range Resolving Power R=λ/Δλ	Field of View Features
EXES	Matthew Richter, UC Davis	Mid-IR Echelle Spectrometer Facility Instrument	4.5 – 28.3 μm R = 1,000 – 10^5	1″ – 180″ slit lengths 1024x1024 Si:As
FIFI-LS	Alfred Krabbe, DSI	Far-IR Imaging Grating Spectrometer Facility Instrument	51 – 200 μm R = 600 – 2,000	30″ x 30″ (Blue) 60″ x 60″ (Red) 2x(16x25) Ge:Ga
FORCAST	Terry Herter, Cornell University	Mid-IR Camera & Grism Spectrometer Facility Instrument	5 – 40 μm R = 100 – 300	3.4′ x 3.2′ 2x(256x256) Si:As, Si:Sb
GREAT	Jürgen Stutzki, University of Cologne	Far-IR Heterodyne Spectrometer PI Instrument	63 – 612 μm R = 10^6 – 10^8	diffraction limited heterodyne receiver
HAWC+	Charles Dowell, JPL	Far-IR Bolometer Camera & Polarimeter Facility Instrument	50 – 240 μm Δλ = 9 – 43 μm	from 1.4′ x 1.7′ (53 μm) to 4.8′ x 6.1′ (214 μm) 3x(32x40) bolometer
FPI+	Jürgen Wolf, DSI	Focal Plane Imager Facility Instrument	0.36 – 1.10 μm R = 0.9 – 29.0	8.7′ x 8.7′ 1024x1024 CCD

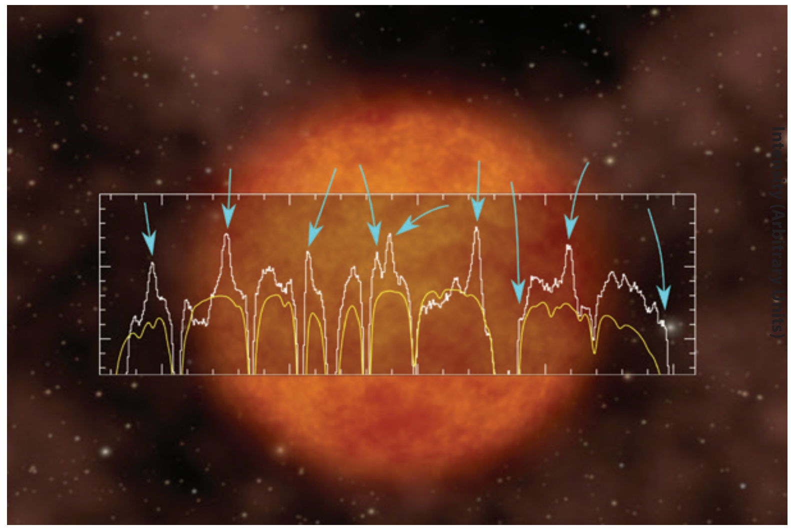
EXES: Echelon-Cross-Echelle Spectrograph

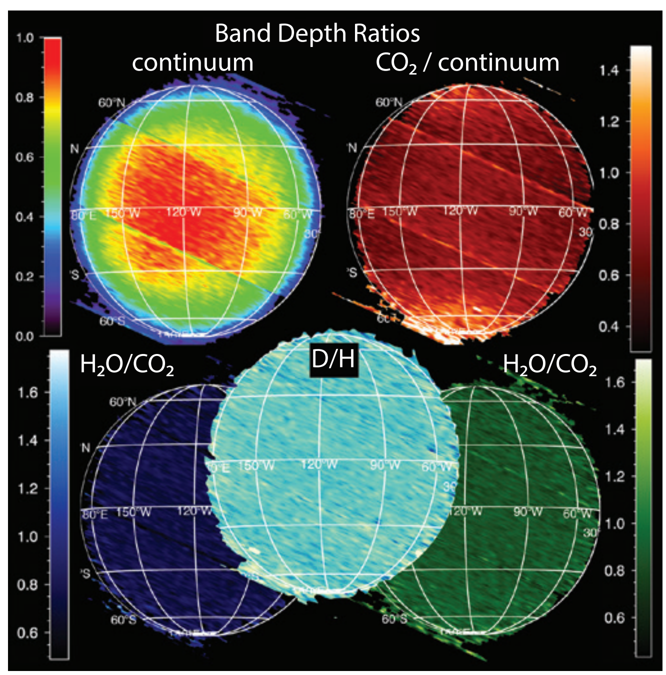
Facility Class, High Res, Mid-Infrared Spectrograph

Principal Investigator: Matthew J. Richter, University of California Davis

Carbon Dioxide in R Leonis

In October 2018, EXES observed the Oxygen-rich asymptotic giant branch (AGB) star R Leonis (R Leo) with high-spectral resolution (R=70,000, 4.3 km/s). In the accompanying figure, a small section of the total spectrum of R Leo is shown in white and the ATRAN model of Earth's atmosphere in yellow. The blue arrows point to the detections of emission from carbon dioxide (CO_2), which are Doppler shifted by about −22 km/s for the time of the observations. The EXES observations represent the first detection of CO_2 towards R Leo and illustrate that EXES/SOFIA can study this important molecule in O-rich AGB stars from within Earth's atmosphere. *(Fonfría et al., 2020, A&A, 643L, 15)*





Venus Spectral Maps

EXES observed Venus with high spectral resolution at 7.2 µm, simultaneously probing the amount of water and (semi) heavy water in its clouds. Relating the D/H ratio to clouds, temperature, global position, and seasons helps to constrain the microphysical models of water-loss used to study the evolution of Venus's atmosphere. Preliminary results show a surprising spatial uniformity to the D/H ratio. Ratio to the CO_2 strength allows us to cancel, to first order, the effects associated with the calibration, the geometry, and atmospheric parameters. *(Tsang, et al., in prep)*

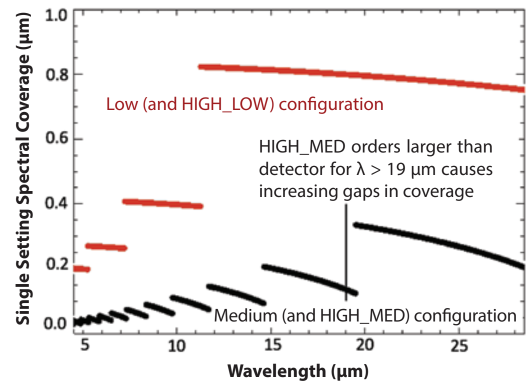
Specifications

EXES features an array dimension of 1024x1024 and a pixel size of 0.2 arcsec. High resolution is provided by an echelon (a coarsely-ruled, steeply-blazed, aluminum reflection grating) along with an echelle grating to cross-disperse the spectrum.

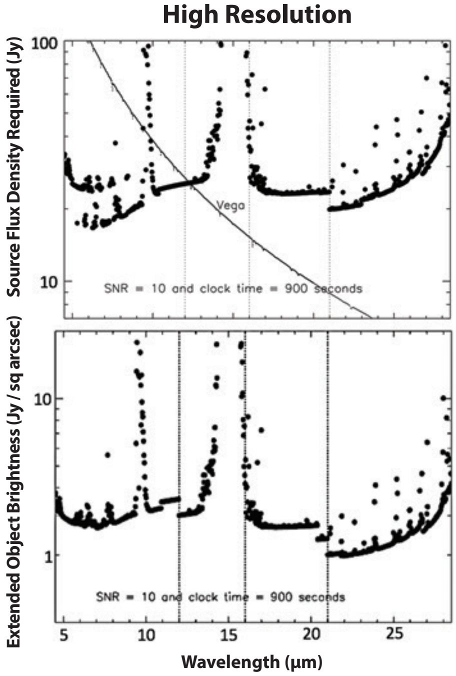
The echelon can be bypassed so that the echelle acts as the sole dispersive element, resulting in single order spectra at medium or low resolution depending on the incident angle.

The available configurations are Low (low resolution), Medium (medium resolution), HIGH_MED, and HIGH_LOW. Configurations are called HIGH_MED if the cross disperser echelle angle is 35–65° and HIGH_LOW for angles between 10–25°. The shorter slits in HIGH_LOW allow for more orders to be packed onto the array, thus increasing the instantaneous wavelength coverage while maintaining the same high spectral resolution as the HIGH_MED configuration.

Spectral Coverage



High Resolution



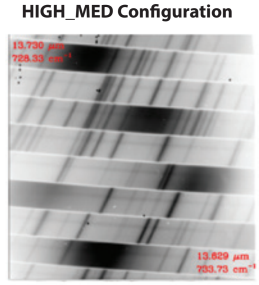
Above: Sensitivities for point *(top)* and extended *(bottom)* sources, assuming nominal conditions.

Spectral Parameters

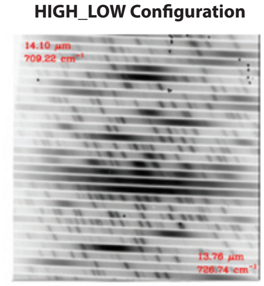
Configuration	Slit Length	Spectral Resolution
Low	25"–180"	1,000–3,000
Medium		5,000–20,000
HIGH_MED	1.5"–45"	50,000–100,000
HIGH_LOW	1"–12"	

In the Medium and Low configurations the slit lengths vary from 25" to 180" depending on the number of rows to be read.

HIGH_MED Configuration



HIGH_LOW Configuration



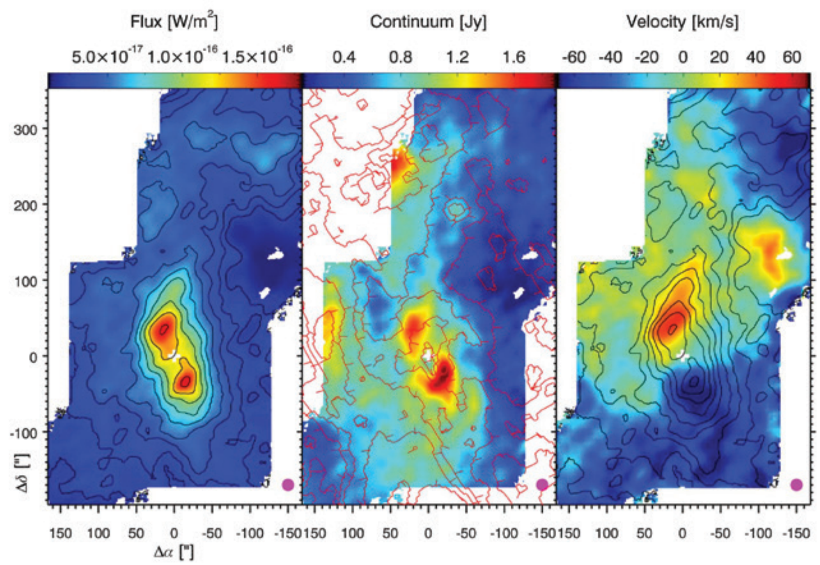
Left: Raw 2D spectra without nod-subtraction to highlight the sky emission lines *(dark)*. Possessing the same spectral resolution, HIGH_LOW has a larger spectral coverage at the expense of a shorter slit.

FIFI-LS: Field Imaging Far-Infrared Line Spectrometer

Facility Class, Integral Field, Far-Infrared Spectrometer

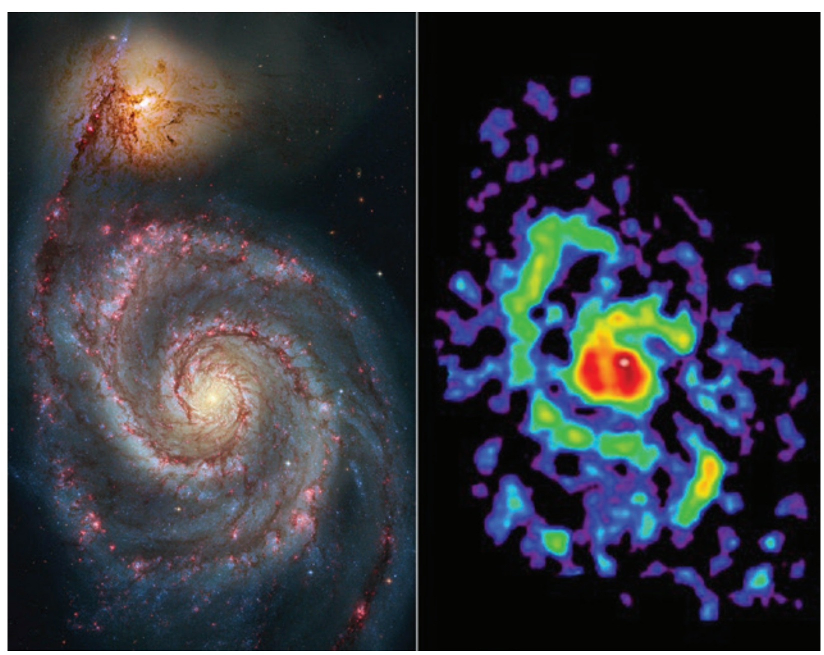
Principal Investigator: Alfred Krabbe, German SOFIA Institute, University of Stuttgart

The Circumnuclear Ring in the Galactic Center



[CII] emission line flux *(left)*, continuum with H_2 shown by red contours *(center)*, and [CII] velocity maps with [CII] line flux shown by black contours *(right)* from fits to FIFI-LS data. The velocity map in the inner 100" shows a rotation-like pattern around Sgr A* with redshifted emission to the north–northeast and blueshifted emission to the south–southwest, aligned with the [CII] emission peaks and the continuum peaks. *(Iserlohe et al. 2019, ApJ, 885, 169.)*

The Whirlpool Galaxy, M51



Optical image from the HST *(left)* and [CII] line flux from FIFI-LS *(right)* showing how the [CII] traces the star formation in the spiral arms of the galaxy with a good correlation seen between star formation surface density and [CII] flux in the central, spiral arm, and inter-arm regions. M51b, at the top of both images, is much fainter in [CII]; this is thought to be a result of suppressed star formation in that galaxy, whose high IR continuum flux is believed to be due to mechanisms other than star formation. *(HST image: NASA, Hubble Heritage Team, (STScI/AURA), ESA, S. Beckwith (STScI). Additional Processing: Robert Gendler. SOFIA image: J.L. Pineda et al. 2018 ApJL, 839, L30; C. Fischer/DSI)*

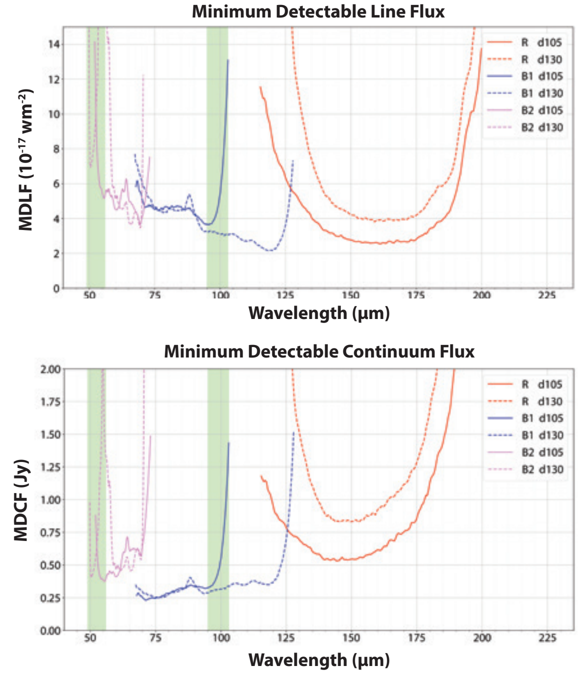
Specifications

FIFI-LS is an integral field, far-infrared spectrometer consisting of two independent grating spectrometers. Each spectrometer has a detector consisting of 400 pixels of Gallium-doped Germanium photoconductors. The projection onto the sky of the 5x5-pixel FOVs of the blue channel and the red channel is nearly concentric (10" offset), but the angular coverage differs. The spectral resolution channels vary between 500 and 2000, depending on the observed wavelength, with higher values reached towards the long wavelength ends of each spectrometer.

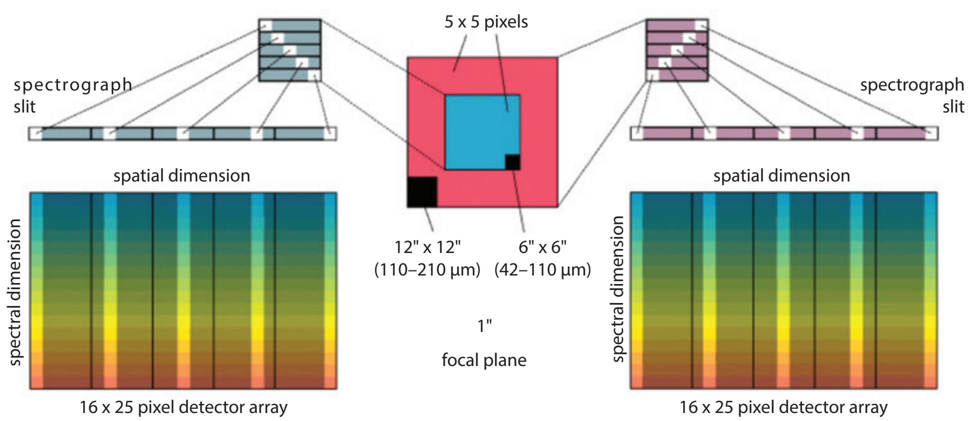
Channel Parameters

Channel	Field of View	Pixel Size	λ Range
Blue	30" x 30"	6" x 6"	51–120 µm
Red	1' x 1'	12" x 12"	115–200 µm

Predicted Sensitivity for SNR = 4 in 900 s

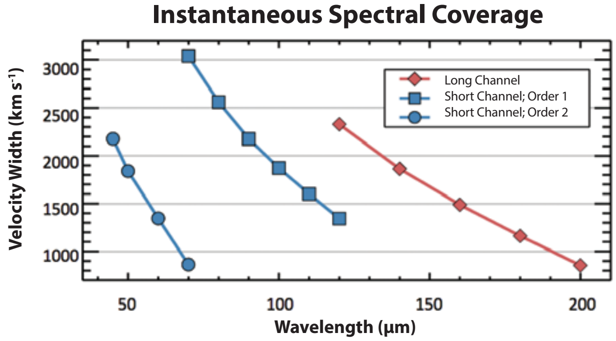


Data Cube

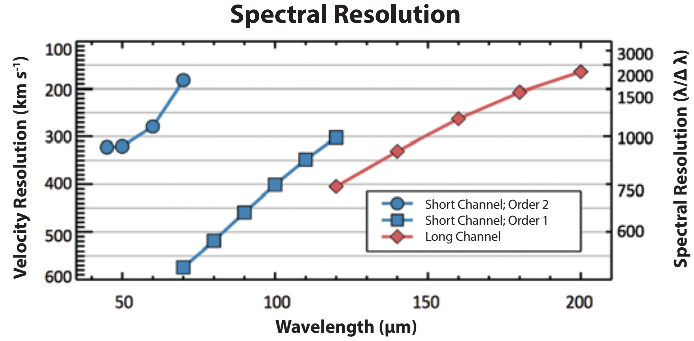


Left: The integral field unit for each channel consists of 15 specialized mirrors to slice the two dimensional 5x5 pixel FOV into five slices that are each five pixels long, which are then reorganized along a one dimensional line (25x1 pixel), forming the spectrometer entrance slit. The diffraction grating disperses the incoming light, which reaches the 16x25 pixel detector array. The result is a "data cube" with 5x5 spatial pixels and 16 pixels in the spectral dimension.

Instantaneous Spectral Coverage



Spectral Resolution



FORCAST: Faint Object InfraRed Camera for the SOFIA Telescope

Facility Class, Mid/Far-Infrared Camera and Spectrograph

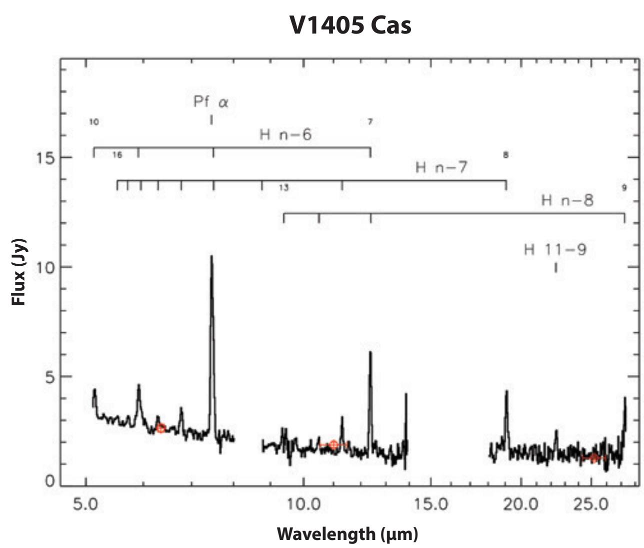
Principal Investigator: Terry Herter, Cornell University

Star Formation Signatures in the Galactic Center

A composite image of the Galactic Center from the Cycle 7 FORCAST Galactic Center Legacy Survey *(Hankins et al. 2020, ApJ, 894, 55)* at 25 µm in blue and 37 µm in green, combined with Herschel data at 70 µm in red and Spitzer data at 8 µm in white. The survey covered 403 arcmin^2 including Sgr A, B, and C complexes. The high spatial resolution afforded by FORCAST and the ability to resolve regions that were saturated with Spitzer allow the study of mid-IR sources and sites of ongoing star formation within the Galactic Center region. The publicly available dataset contains images of regions with the most extreme conditions of star formation in our galaxy and reveal extended features, structures in the Arched Filaments and Sickle H II regions, hints of ongoing star formation in Sgr B2 and C, and isolated star formation activity. The angular resolution and details visible in these FORCAST images of the Galactic Center provided by the Legacy program are unrivaled and unprecedented at these wavelengths.

Grism Coverage 5–27 µm

Spectra, obtained with three of the four grisms (G063, G111, and G227) in FORCAST and spanning 5–27 µm at low spectral resolution (R~120–140), of the very slow, bright nova V1405 Cas. These data reveal the full suite of hydrogen recombination lines labelled to the right. The absence of forbidden metallic emission lines ~105 days after the outburst began (March 18, 2021) suggests the density in the ejecta is sufficiently high to quench the lines. The relative line strengths and shape of these spectra are notably similar to those of nova V339 Del *(Gehrz, R. D., et al. 2018, ApJ, 812, 132)*. The red points are the photometric results from FORCAST filter images, demonstrating the accuracy of the spectroscopic flux calibration. *(Gehrz et al. 2021, ATel, 14794)*



Specifications

The short wavelength channel (SWC) and long wavelength channel (LWC) can be used individually or together for simultaneous imaging of the same field of view. For grism observations, either channel may be used independently.

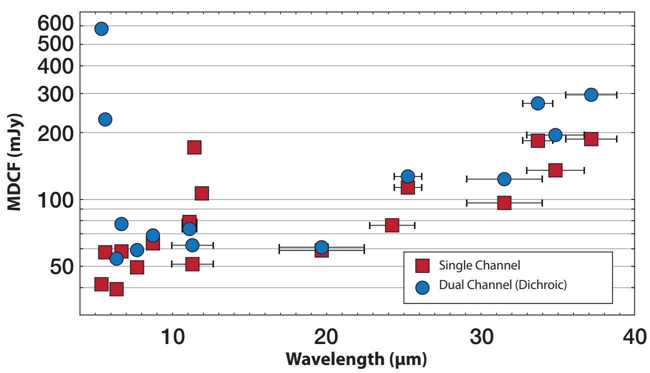
Camera Details

Camera	Wavelength Range	Detector
SWC	5–25 μm	Si:As (BIB)
LWC	25–40 μm	Si:Sb (BIB)
Each channel consists of a 256x256 pixel array that yields a 3.4'x3.2' instantaneous field-of-view with 0.768" pixels		

Imaging

The point spread function (PSF) in FORCAST images is consistent with the telescope's diffraction limit convolved with the 1.3" rms jitter. In dual channel mode, a dichroic is used to split the beam into the SWC and LWC, decreasing the throughput of the system by 40–85% relative to the single channel mode.

FORCAST Sensitivity



Continuum point source sensitivities for single and dual channel modes. Values are for S/N = 4 in 900 s under nominal conditions. Investigators are encouraged to use the SOFIA Integration Time Calculator (SITE) for their calculations.

Filter Parameters

SWC Filters		LWC Filters	
λ_{eff} (μm)	Δλ (μm)	λ_{eff} (μm)	Δλ (μm)
5.4	0.16	11.3	0.24
5.6	0.08	11.8	0.74
6.4	0.14	24.2	2.9
6.6	0.24	31.5	5.7
7.7	0.47	33.6	1.9
8.8	0.41	34.8	3.8
11.1	0.95	37.1	3.3
11.2	2.7	A subset of these will be chosen each cycle as the nominal set.	
19.7	5.5		
25.3	1.86		

Spectroscopy

FORCAST grisms provide coverage from 5–40 μm. Blazed diffraction gratings are used in transmission and stacked with blocking filters to prevent order contamination. Two long slits (2.4"x191", 4.7"x191") are available.

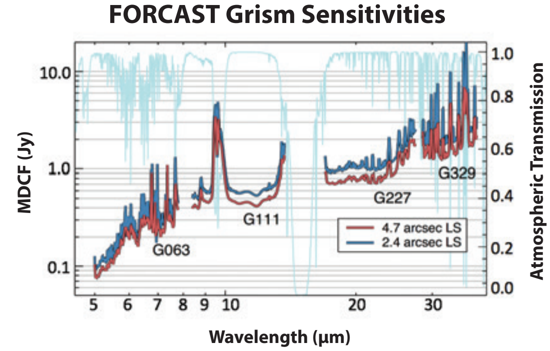
Grism Details

Grism	Coverage (μm)	R (λ/Δλ)[a]
G063	4.9–8.0	120[b]/180
G111	8.4–13.7	130[b]/260
G227	17.6–27.7	110/120
G329	28.7–37.1	160

[a] For the 4.7"x191" and the 2.4"x191" slits, respectively.

[b] The resolution of the long, narrow-slit modes is dependent on (and varies slightly with) the in-flight IQ.

FORCAST Grism Sensitivities



Grism continuum point source sensitivities for both wide and narrow long slits overlaid on an atmospheric transmission model (light blue). Values are for S/N = 4 in 900 s under nominal conditions.

FPI+: Focal Plane Imager Plus

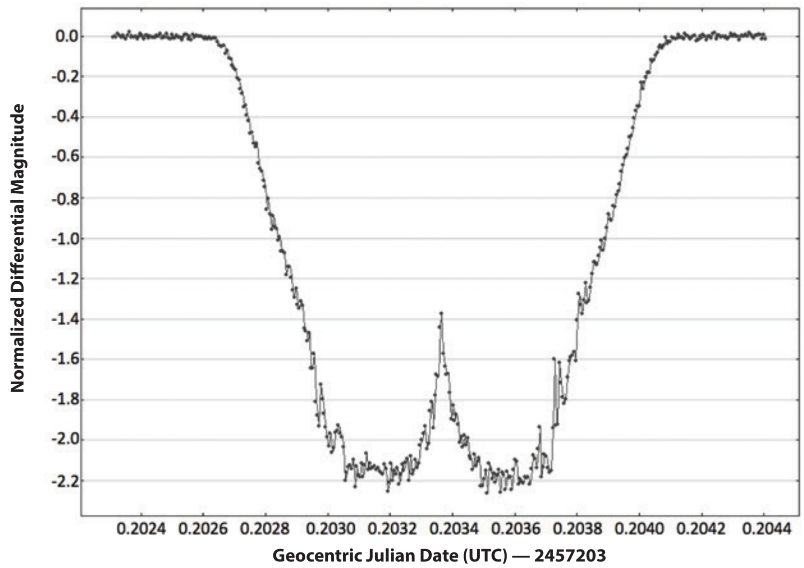
Fast Frame Rate Optical Photometer

Principal Investigator: Jürgen Wolf, DSI

Pluto Stellar Occultation

The 2015 stellar occultation by Pluto of a background star with an r-band of magnitude ~12 was captured by FPI+ as a light curve, showing the decreased signal (in magnitudes) during the event. The central flash in the middle of the light curve confirms the precise position of SOFIA on the centerline of the shadow path, allowing for analysis of the upper atmosphere. This results in a best-fit value for the occultation half-light radius of 1288±1 km (i.e., the radius in the atmosphere at which the occultation light curve drops to half its original flux due to refraction). *(Bosh et al. 2016, submitted.)*

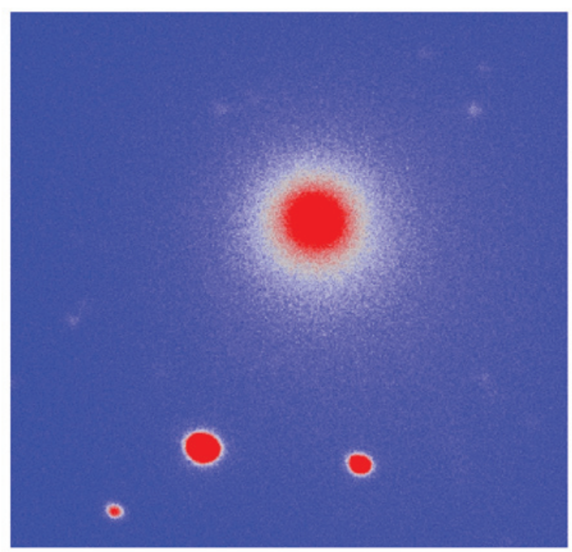
Stellar Occultation by Pluto 2015-06-29
SOFIA FPI+ Data



C2013 US10 Catalina Coma

FPI+ produced an I-band image of Comet C2013 US10 Catalina as part of a combined infrared and visual observation. The comet's coma is nicely visible in comparison to the more compact stars toward the bottom of the image. *(C. E. Woodward et al.)*

I-band Image of Comet C2013 US10 Catalina



Specifications

FPI+ is the upgrade to FPI with a science grade CCD. More than 50% of the light detected onboard SOFIA between 480 nm and 800 nm is transmitted to FPI+, the range at which the camera is most sensitive. The CCD sensor is an e2v CCD 201-20 1024x1024 pixel frame transfer EMCCD with the specifications given in the Optical Properties table *(right)*.

Six spectral filters are available, including five Sloan Digital Sky Survey filters u′, g′, r′, i′, z′, and a Schott RG1000 near-IR cut-on (Daylight) filter. The Sloan u′ filter has a very low throughput (~0.5%) because other optical elements in the FPI+ light path are nearly opaque at this wavelength. There are an additional three neutral density (ND) filters that can be used to attenuate bright stars.

The filters are installed in a double-carousel filter wheel with six positions in each carousel, a list of which is given in the Filter Suite table *(right)*. Filters from Carousel 1 and Carousel 2 can be combined freely with a few exceptions.

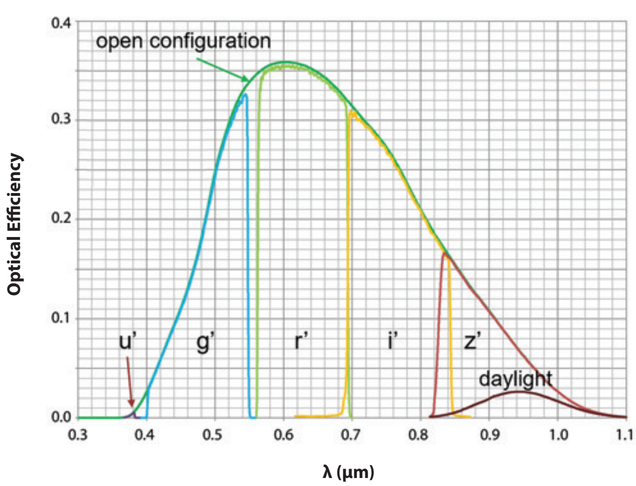
Optical Properties

Field of View	λ Range	Plate Scale
8.7' x 8.7'	360–1100 nm	0.51" per pixel

Filter Suite

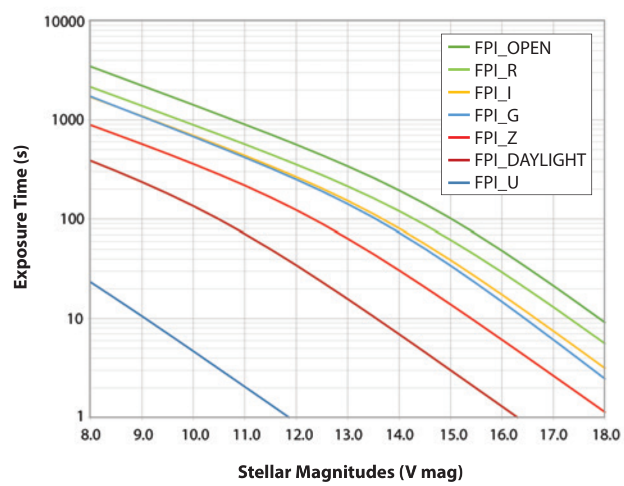
Carousel 1	Carousel 2
OPEN	OPEN
Sloan u′	ND 1
Sloan g′	ND 2
Sloan r′	ND 3
Sloan i′	Daylight
Sloan z′	Blocked

Filter Throughput



Plot of the optical efficiency for five spectral filters and the OPEN FPI+ configuration. The plot includes the calculated SOFIA telescope throughput, the instrument quantum efficiency, and the measured filter spectral response.

Sensitivity



Signal to Noise Ratio for point sources imaged unbinned with FPI+ at t_EXP = 1 sec. Displayed is the OPEN configuration as well as the spectral Sloan filters u, g, r, i, z, and the daylight NIR cut-on filter.

GREAT: German REceiver for Astronomy at Terahertz Frequencies

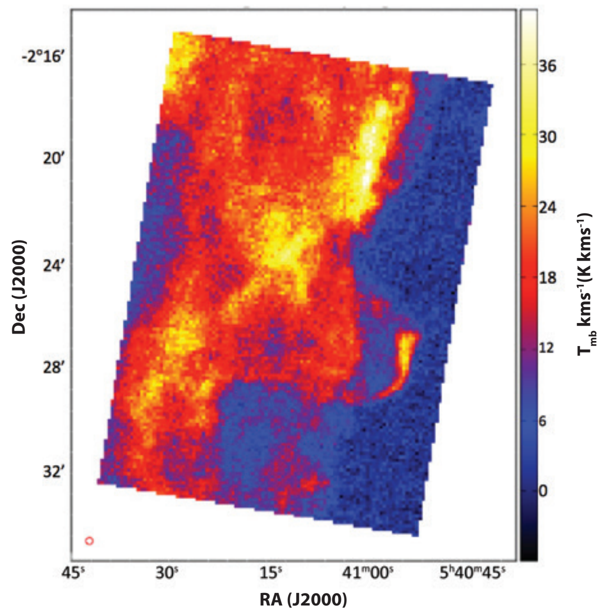
Principal Investigator Class, Far-Infrared, Multi-Pixel Spectrometer

Principal Investigator: Jürgen Stutzki, University of Cologne

Horsehead Nebula Velocity Resolved Map

A velocity resolved map of the iconic Horsehead Nebula in the [C II] 158 μm line was obtained by the upGREAT Low Frequency Array (LFA). The [CII] line is one of the strongest cooling lines in the interstellar medium, and here it traces the photodissociation region illuminated by the O9.5V star Sigma Orionis. The integrated intensity image is shown in the figure to the right. The 12'x17' map, encompassing the nebula and the underlying cloud ridge, was obtained in just over four hours of observation on a single flight. The angular resolution of the map is 15.1" and the velocity resolution is 0.19 km/s (R > 10^6). These remarkably efficient observations were made possible by an increase in the sensitivity of the upGREAT detectors with the use of fourteen independent detectors of the LFA, and the increased mapping speed facilitated by SOFIA's inertially stable platform.

Horsehead C+ Emission
Integrated Velocity Range from 9.5 to 11.5 km/s

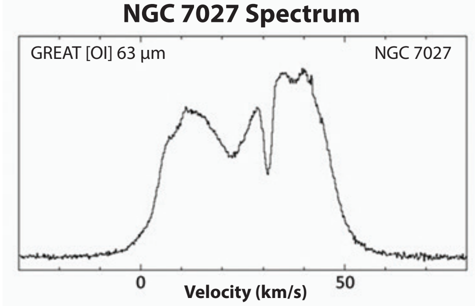


Data publicly available in the SOFIA Science Archive.

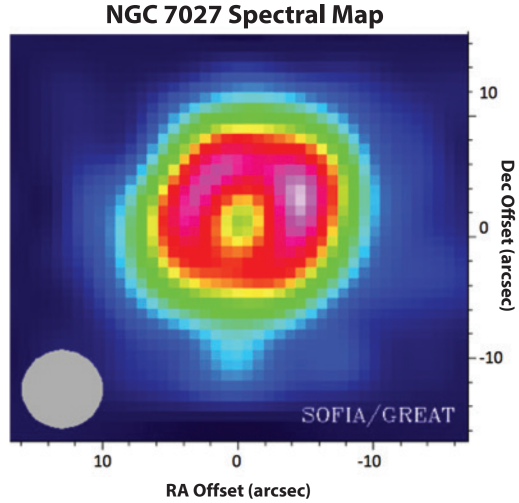
Planetary Nebula NGC 7027

Spatial scans made by the GREAT spectrometer's H-channel receiver enabled the production of a spectral map and integrated spectrum for Planetary Nebula NGC 7027 in the [OI] 63 μm line. The effective angular resolution is indicated by the gray circle. The high-resolution spectrum displays the characteristic shape for an expanding, optically thin shell. The complex line structure shows that the expanding nebula has multiple components moving at different velocities. *(GREAT Consortium)*

NGC 7027 Spectrum



NGC 7027 Spectral Map



Specifications

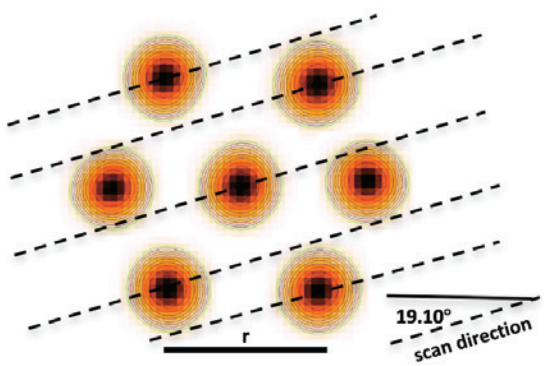
GREAT supports the following Astronomical Observing Templates (AOTs): Single Point, Raster Map, On-the-Fly map, On-the-Fly Array map, and On-the-Fly Honeycomb map. Each AOT is run in either of two observing modes: Total Power or Beam Switching.

Observing Modes

Total Power: The telescope moves between a target and a nearby emission-free reference position.

Beam Switching: The secondary mirror chops between the source and a nearby reference position at a rate of ~1–2.5 Hz. The telescope nods between these positions at a slower rate than when chopping.

LFA & HFA Pixel Arrays



A generalized hexagonal pattern of the LFA and HFA. The spacing between pixels, r, is slightly more than two beam widths at ~31.7" for LFA and 13.8" for HFA.

upGREAT and 4GREAT Receivers

The upGREAT Low Frequency Array (LFA) is a dual polarization, 2x7 pixel array operating at 1.835–2.065 THz, and the upGREAT High Frequency Array (HFA) is a 1x7 pixel array operating at 4.74477749 THz. In On the Fly mode, upGREAT can observe extended regions of the sky efficiently, as shown by the Horsehead Nebula map on the previous page.

4GREAT has four single-pixel channels that observe the same position on the sky simultaneously. Their central frequencies are 0.43, 1.00, 1.37, and 2.54 THz. The GREAT instrument uses eXtended bandwidth Fast Fourier Transform Spectrometers (XFFTS) as backends. Each XFFTS has a bandwidth of 4 GHz and 16,384 channels with a frequency resolution of 244 kHz. At the [CII] line frequency of 1.9 THz, this corresponds to a channel spacing of ~0.04 km/s.

GREAT can be run with the configurations upGREAT LFA with upGREAT HFA or 4GREAT with upGREAT HFA.

Channel Parameters

Channels	Frequency Range [THz]	T_{rec} Double Sideband	FWHM	Astronomical Lines of Interest
upGREAT HFA	4.7447 +/– 100 km/s	1250 K	6"	[OI]
upGREAT LFA-H	1.835–2.007	1000 K	15"	[CII], CO, $OH^2\pi_{1/2}$
upGREAT LFA-V	1.835–2.007 2.060–2.065	1000 K	15"	[OI], [CII], CO, $OH^2\pi_{1/2}$
4GREAT	2.490–2.590	3300 K	12"	$OH^2\pi_{3/2}$, $^{18}OH^2\pi_{3/2}$
	1.240–1.395 1.427–1.525	1100 K	19"	[NII], CO, OD, HCN, SH, H_2D^+
	0.890–0.984 0.990–1.092	>600 K 300 K	25"	CO, CS
	0.491–0.555 0.560–0.635	<150 K	50"	NH_3, [CI], CO, CH

HAWC+: High-resolution Airborne Wideband Camera Plus

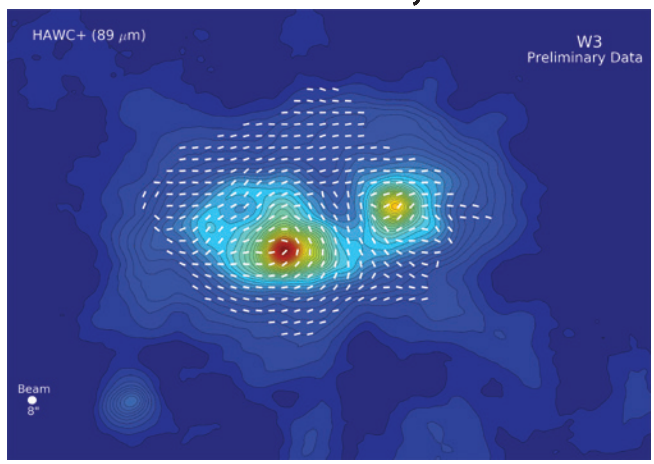
Facility Class, Far-Infrared Camera and Polarimeter

Principal Investigator: C. Darren Dowell, Jet Propulsion Laboratory

Star Forming Region W3

The structure of the far-infrared polarization in the W3 star forming region, as observed by HAWC+ at a wavelength of 89 μm. Each line segment represents the orientation of polarization at that location overlaid on an image of the total intensity at the same wavelength. Vectors represent the electric field direction. For clarity, only one-quarter of the polarization measurements are shown and the line segments are set to a fixed length. The polarization is caused by the partially oriented radiation from elongated dust grains that are aligned with the magnetic field in the cloud. *(HAWC+ Team)*

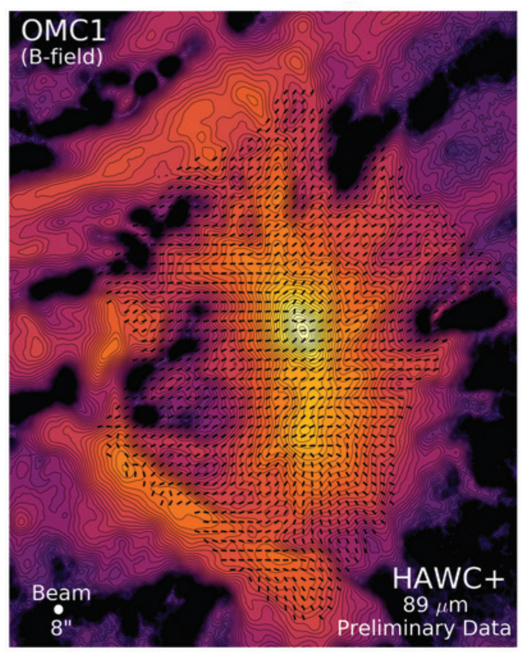
W3 Polarimetry



Star Forming Region Orion

HAWC+ performed polarization measurements at 89 μm to capture the structure of the magnetic field in the Orion star forming region. Each line segment represents the orientation of the magnetic field at that location, overlaid on an image of the total intensity at the same wavelength. The total intensity image has a pixel scale of 1.5 arcsec per pixel and the polarization results were smoothed to a scale of 8 arcsec per pixel to produce statistically independent vectors in this HAWC+ observing band. For clarity, the line segments are set to a fixed length. *(HAWC+ Team)*

Orion Polarimetry

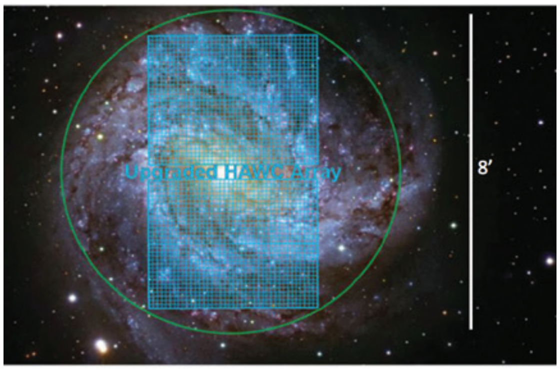


Specifications

HAWC+ offers both total intensity imaging and imaging polarimetry in five bands ranging from 50 to 240 µm. Nod match chop observing mode is used for imaging polarimetry and a number of efficient scan modes are available for total intensity imaging.

For all observing modes, a wire grid reflects one component of linear polarization and transmits the orthogonal component to two comounted detector arrays. A single detector array provides a field of view (FOV) of 32x40 pixels for imaging polarimetry and the two detectors combined yield a 64x40 pixel FOV for total intensity imaging. The detectors are designed to deliver background-limited observations with high quantum efficiency for all the HAWC+ continuum bands.

64x40 HAWC+ Array Footprint



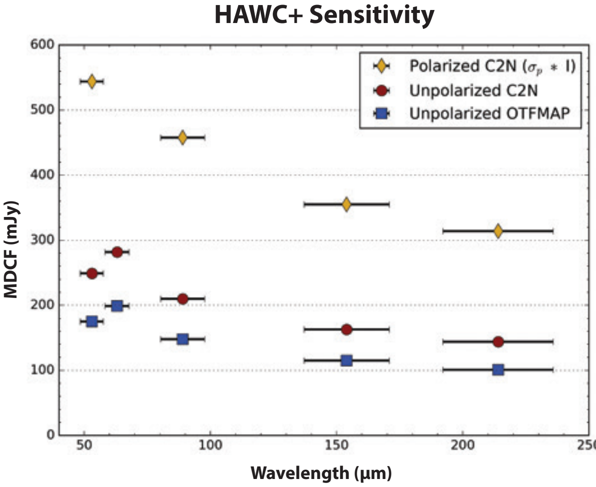
Footprint for total intensity imaging observations using the 64x40 pixel array in Band E. A 32x40 pixel FOV is available for imaging polarimetry observations.

Instrument Parameters for Bands A–E

Band/ Wavelength	Δλ	Angular Resolution	Total Intensity FOV (arcmin)	Polarization FOV (arcmin)
A / 53 µm	8.70	4.85" FWHM	2.8 x 1.7	1.4 x 1.7
B[a] / 63 µm	8.90	10.5" FWHM	4.2 x 2.7	2.1 x 2.7
C / 89 µm	17.00	7.8" FWHM	4.2 x 2.7	2.1 x 2.7
D / 154 µm	34.00	13.6" FWHM	7.4 x 4.6	3.7 x 4.6
E / 214 µm	44.00	18.2" FWHM	8.4 x 6.2	4.2 x 6.2

[a]Band B (63 µm) will be offered as shared-risk during Cycle 10.

HAWC+ Sensitivity



Sensitivity estimates in units of the Minimum Detectable Continuum Flux (MDCF) into a single beam. Values take into account all expected overheads. For polarization, the plotted data show the polarized intensity *p x I*, where *p* is the fractional polarization.

Predicted Performance for Continuum Imaging and Polarimetry

Instrument Parameter	Band A	Band B[f]	Band C	Band D	Band E
NESB[a] (MJy sr^{-1} $h^{1/2}$)	18.8	11.4	6.3	1.6	0.8
MDCF[b] (mJy)	250	400	300	260	230
Mapping Speed[c]	0.0027	0.0290	0.029	1.10	7.0
MDCPF[d] (Jy)	80	150.0	50	50	50
MIfP[e] (MJy sr^{-1} $h^{1/2}$)	28,000	17,000	6,000	2,000	1,300

[a]Noise Equivalent Surface Brightness for S/N=1 into a single beam.
[b]Minimum Detectable Continuum Flux for a point source with S/N=4 in 900s.
[c]Real scan rate required to achieve a given NESB. Units: $arcmin^2$ h^{-1} (MJy sr^{-1})$^{-2}$
[d]Minimum Total Continuum Flux for a point source required to measure the polarization fraction to an uncertainty level of $\sigma_p < 0.3\%$ with a SNR (in the polarization fraction)≥4 in 900s
[e]Minimum total Intensity required to measure Polarization to an uncertainty level $\sigma_p \leq 0.3\%$. All chop/nod and polarization overhead values have been applied to this value.

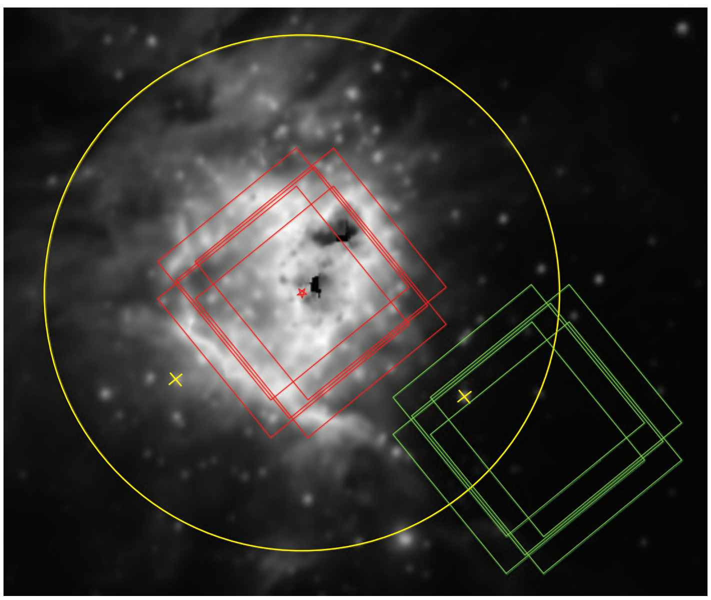
Proposal Resources

SOFIA offers the following tools and documentation to facilitate the proposal process.

Core Documentation

The Call for Proposals (CfP) solicits observing proposals from the U.S. and international astronomy communities. The document describes how to prepare and submit proposals, including details on how proposals will be evaluated, and formally establishes the policies and rules governing SOFIA operations for the relevant cycle.

The Observer's Handbook is the primary technical reference for astronomers who wish to submit a proposal in response to the CfP, providing detailed information about the instruments and observing modes that will be available for observations during the relevant cycle.



Above: USPOT visualization of the Orion Nebula with the FORCAST field of view (FOV) overlaid on an archival WISE Band 1 image. Shown are the FPI+ FOV *(yellow circle)*, FPI+ guide stars *(yellow crosses)*, FORCAST dithers on-source *(red boxes)*, and FORCAST asymmetric chopped dithers off-source *(green boxes)*. Chopping on- and off-source is an observing technique used to remove background emission from the sky. While the WISE image is heavily saturated, FORCAST has a dynamic frame rate that prevents these saturation effects.

Proposal Submission Tools

All SOFIA proposals are prepared and submitted using the Unified SOFIA Proposal and Observation Tool (USPOT). USPOT contains many built-in features to help with planning observations, such as the Target Visibility tool that can be used to determine which time of year the target is most visible from the takeoff location of SOFIA. The USPOT Manual guides users through the procedures for submitting proposals for SOFIA, with specific instructions for each instrument.

The observatory provides additional tools to aid in the proposal submission process.

Estimations of exposure times for each instrument can be made using the SOFIA Instrument Time Estimator (SITE), a web-based tool that provides total integration time or S/N for a given instrument, filter(s), source type (point, extended, emission line), and water vapor overburden.

The atmospheric transmission as a function of wavelength may be obtained using the online tool ATRAN. The use of ATRAN is necessary for planning SOFIA high-resolution spectroscopic observations.

The observatory hosts webinars and workshops prior to the start of each observing cycle to guide users through using these resources to submit proposals. Sign up for the e-Newsletter and check the SOFIA website for announcements of upcoming events.

Data Resources

The following tools and documentation are available for utilizing and analyzing SOFIA data. These resources are available on the Science Center website and on GitHub.

Public Archival Data

The SOFIA Science Center provides raw and calibrated data for the entire instrument suite. The level of data processing ranges from corrections for instrument artifacts, to flux calibrated and telluric corrected data, to maps and mosaics. These data are publicly available for further exploration after their exclusive use periods expire.

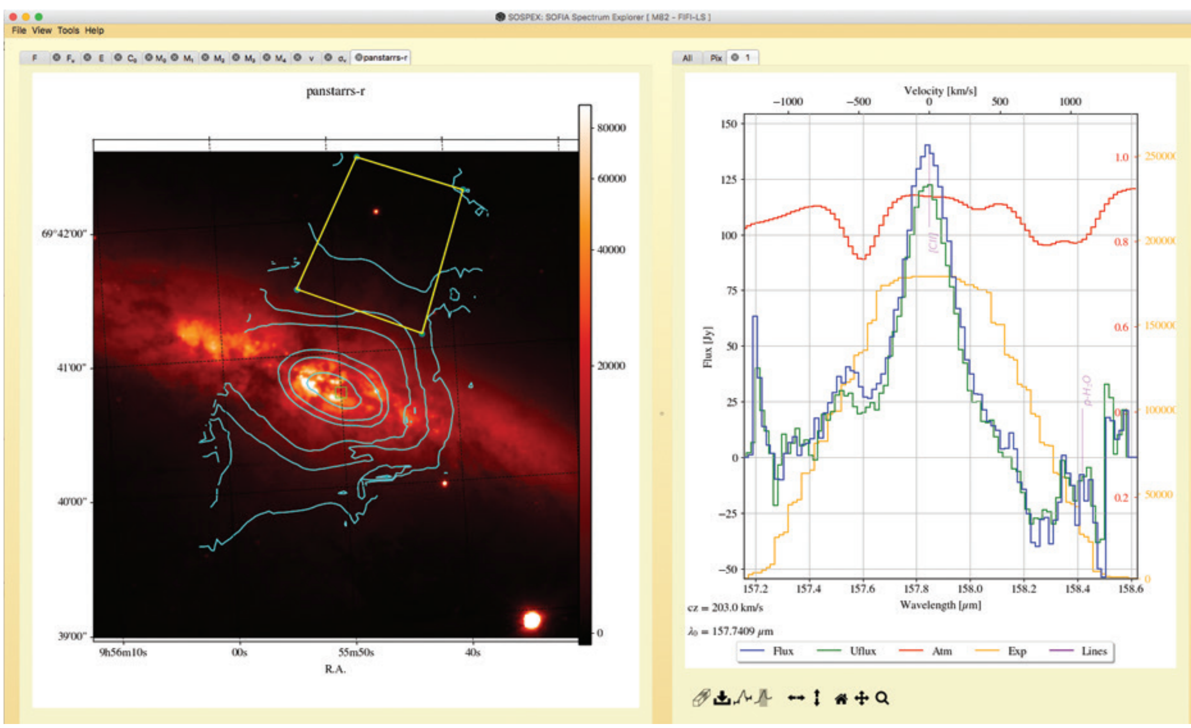
The observatory has transitioned from storing data in the SOFIA Data Cycle System (DCS) to the IPAC Infrared Science Archive (IRSA), which has become the primary data archive. Access the SOFIA webpage on IPAC at https://irsa.ipac.caltech.edu/Missions/sofia.html

Data Analysis

Detailed data analysis can be accomplished by using custom software provided by the observatory.

Data cubes are three-dimensional matrices with two spatial axes (right ascension and declination) and a wavelength axis. The FLUXER tool can be used to fit the continuum and estimate line strengths in final data cubes. Furthermore, the SOFIA SPectral EXplorer (SOSPEX) allows users to probe spectral cubes produced by the data reduction pipeline.

Data analysis tutorials are available to guide new and experienced users through performing aperture photometry, emission line analysis, custom spectral extraction, finding sample data sets, and other common data analysis objectives using SOFIA processed data.



The SOFIA SPectral EXplorer (SOSPEX) tool analyzing FIFI-LS spectral data cubes produced from C+ observations of the starburst galaxy, M82.

www.sofia.usra.edu