The *Stratospheric Observatory for Infrared Astronomy* (*SOFIA*) – Current Status, Recent Results, Future Plans, and Synergies with the *AKARI* Archive

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ABSTRACT

The Stratospheric Observatory for Infrared Astronomy comprises a 2.7m diameter telescope mounted in a heavily modified B747SP aircraft. The *SOFIA* program is a joint US NASA and German DLR program, with the development and operations costs split roughly 80%:20%, respectively. Although the observatory is funded by these two nations, its observing time is open to proposals from astronomers of any nationality. The observatory has been flying and taking scientific data since 2010 and currently observes astronomical targets from the stratosphere for approximately 800 research flight hours per year. Six science instruments (with an seventh coming online in 2019) cover the visible to sub-millimeter wavelengths with a variety of spectral resolving powers ranging up to 1×10^8. The *AKARI* Archive with its 1.7 to 180 μm wavelength coverage is a natural complementary source for follow-up observations with *SOFIA*. This presentation will cover the current *SOFIA* technical capabilities and will present a few recent science highlights that demonstrate the *SOFIA*/*AKARI* complementarity. The presentation will also cover the *SOFIA* proposal process and will summarize other partnership opportunities for additional observing time on *SOFIA*.

Keywords: NASA Space Missions

1. INTRODUCTION

The NASA/DLR *Stratospheric Observatory for Infrared Astronomy* (*SOFIA*, https://www.sofia.usra.edu/) consists of a Boeing 747-SP aircraft housing a 2.7-meter diameter telescope (Figure 1) designed to make sensitive measurements of a wide range of astronomical objects at wavelengths from 0.3 μm to 800 μm. *SOFIA* is designed and planned for at least two decades of operations and joins the *Spitzer Space Telescope* (Werner et al. 2004), the *Herschel Space Observatory* (Pilbratt 2003), the *James Webb Space Telescope* (*JWST*, Gardner et al. 2006) and the *AKARI* mission (Murakami et al. 2007) as one of the primary facilities for observations in the thermal IR and sub-millimeter wavelength range. Furthermore, *SOFIA* will be a test bed for new technologies and a training ground for a new generation of instrumentalists. *SOFIA* is funded jointly by NASA and the German Space Agency (DLR), with the two agencies splitting the operational costs and science time usage by 80% and 20%, respectively. The Universities Space Research Association (USRA) and the Deutsches *SOFIA* Institut (DSI) in Stuttgart, Germany manage science and mission operations for NASA and DLR.

2. THE *SOFIA* OBSERVATORY

SOFIA is a near-space observatory that comes home after every flight. Its great strength is that science instruments can be adjusted, repaired, and exchanged regularly to accommodate changing science requirements and new technologies that do not have to await space qualification. Furthermore, large, massive, complex and sophisticated instruments with substantial power needs and heat dissipation can be flown on *SOFIA*. The portability of *SOFIA* is a unique and key enabling aspect of the mission. Since it can operate from other airfields when necessary, it can conduct observations at any declination and respond promptly to transient and location specific events such as variable stars, comets, occultations, eclipses, novae and supernovae. *SOFIA* can observe important astrophysical events even when they occur close enough to the Sun to be unobservable from space missions.

Flying at altitudes up to 45,000 feet (13.72 km) where the typical precipitable atmospheric water column overburden is less than 10 μm (a hundred times lower than at good terrestrial sites), *SOFIA* observes at wavelengths from 0.3 μm through the sub-millimeter spectral region with an average transmission better than 80% (Figure 2). As such, *SOFIA* will

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Figure 1. An unusual picture of the *SOFIA* observatory in flight with the telescope door open in the daytime. The *SOFIA* observatory does not generally fly with the door open while the sun is up in order to mitigate the risk of focused sunlight inside the telescope cavity. When this picture was taken the telescope's primary mirror was covered with a protective tarp that was developed for open-door aircraft flight testing.

allow observations in large parts of the spectrum that are completely inaccessible from the ground. Although some strong water absorption lines remain, the pressure broadening is much reduced so that high resolution spectroscopy is possible between these lines, enabling science observations at wavelengths that can only be observed with space-based platforms or high-altitude balloon platforms.

3. THE *SOFIA* TELESCOPE

The *SOFIA* telescope, supplied by DLR, is a bent Cassegrain with a 2.7m (2.5m effective aperture) parabolic primary mirror and a 0.35m diameter hyperbolic secondary mirror. The telescope feeds two f/19.6 Nasmyth foci about 300 mm behind the instrument flange , the IR focus and a visible light focus for guiding, that are fed respectively by a gold coated dichroic and an aluminum coated flat. The secondary mirror provides chop amplitudes of up to ±5 arcmin between 0 and 20 Hz. The visible beam is fed into the Focal Plane Imager (FPI), an optical focal plane guiding system which can also be sued as a visible light science instrument for transits. Independent of the FPI there are two other optical imaging and guiding cameras available - a Fine Field Imager (FFI) and a Wide Field Imager (WFI). Both the FFI and WFI cameras are attached to the front ring of the telescope. These three guiding cameras represent increasingly large fields of view, and pointing control accuracy. The telescope has an unvignetted elevation range of 20-60 degrees. The cross-elevation travel is only ±3 degrees, so the airplane must be steered to provide this telescope movement. This latter requirement dictates that flight plans be developed to meet the science needs of each specific scientific observational program. The focal plane instruments and the observers are on the pressurized side of the 6.4m diameter pressure bulkhead on which the bearing is mounted, allowing a shirt-sleeve working environment for the researchers and crew.

4. INSTRUMENTS

Six science instruments are currently available to be mounted on the *SOFIA* telescope: High-speed Imaging Photometer for Occultations (HIPO); Faint Object InfraRed CAmera for the *SOFIA* Telescope (FORCAST); German Receiver for Astronomy at Terahertz Frequencies (GREAT); First Light Infrared Test Experiment CAMera (FLITECAM); Far-Infrared Field-Imaging Line Spectrometer (FIFI-LS); Echelon-Cross-Echelle Spectrograph (EXES). A seventh instrument, the High Resolution Mid-Infrared Spectrometer (HIRMES), is currently in development and is expected to achieve first

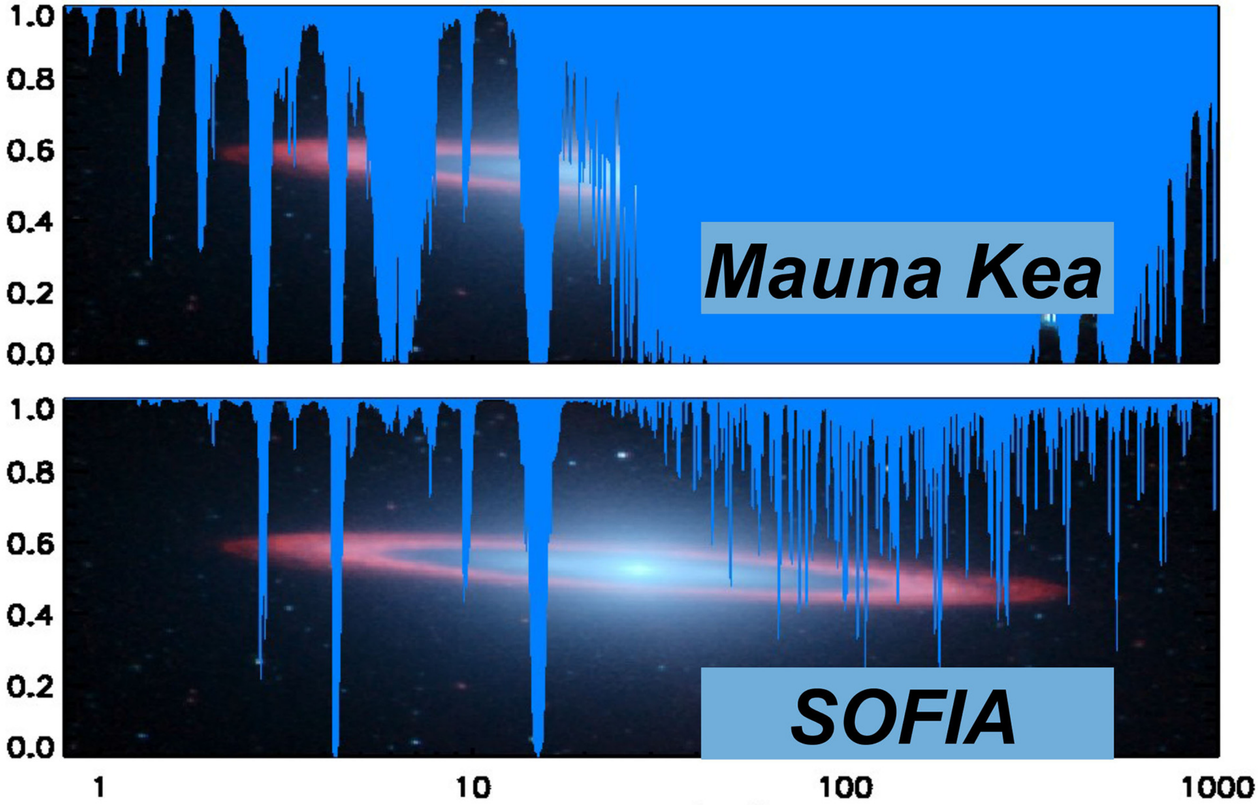

Figure 2. The atmospheric transmission to the Zenith as a function of wavelength at a dry mountain site (top) and from *SOFIA*'s operational altitude (bottom).

light in 2019. Only the HIPO and FLITECam instruments can be co-mounted at the same time. The Focal Plane Imager is sensitive enough that it can also collect useful visible wavelength science data at the same time that any of the instruments are mounted. The spectral resolutions and wavelength coverage of the instruments are shown in Figure 3. The *SOFIA* instrument point-source sensitivities are shown in Figure 5. Changing instruments typically takes two days, with occasionally a third day required for ground checkout of the newly-installed instrument. Further details of the current suite of *SOFIA* instruments can be found on the *SOFIA* mission web site (https://www.sofia.usra.edu/science).

The raw instrument science data is processed through pipelines at either the *SOFIA* Science Mission Operations Center at NASA Ames research Center or by the instrument development teams. Reduced science data that has the instrumental artifacts removed and is flux-calibrated is generally available to the observer within a few weeks of the end of the science campaign that uses that instrument. Once the reduced data is delivered to the observer they have a one-year period of exclusive access to that data before it becomes publicly available to the entire science community on the *SOFIA* Science Archive.

5. OPERATIONS

The *SOFIA* Science and Mission Operations Center (SSMOC) is responsible for the science productivity of the mission, and is located at NASA Ames Research Center in Moffett Field, CA. Flight operations are generally conducted out of NASA Armstrong Flight Research Center's Aircraft Operations Facility in Palmdale, California, USA, although *SOFIA* operates out of Christchurch, New Zealand, for a couple months during their local winter to conduct observations of Southern Hemisphere objects such as the Galactic Center and the Magellanic Clouds. *SOFIA* flights are typically 10 hours in length from takeoff to landing, with approximately 8 hours of this duration used in science observations. As the aircraft has to be steered along a set flight direction to observe a target, flights are composed of multiple legs along a jagged but closed path beginning and ending at the base airfield (Figure 4). Normally the *SOFIA* Program plans for approximately 100 science flights per year.

Science flights are organized into separate flight campaigns with one instrument installed on the telescope. Even with a rotating set of flight crew of pilots, flight engineers, navigators, mission directors, and telescope operators, crew rest limitations and the fuel budget generally limit the the number of flights in a week to three, with a fourth day potentially available as a contingency in the event that one of the flights is scrubbed due to bad weather or an aircraft malfunction. In addition to the professional *SOFIA* staff, successful guest observers can fly on the flights where their data are being acquired.

The *SOFIA* aircraft and telescope require maintenance that can take longer than the normal interval between science flights, and unlike with commercial airlines there are no spare aircraft and telescopes that can be rapidly swapped out while this is being done. As a result there are typically four maintenance downtimes in each year where the plane is grounded while this work is done.

6. OPPORTUNITIES FOR OBSERVERS

Use of the *SOFIA* observatory is open to all qualified astronomers, from both within and outside the U.S. and Germany. Prospective users from U.S. and foreign proposers respond to an annual call for proposals, typically issued in the late spring/early summer of the year. There are two solicitations, one for proposers from U.S. and all non-German foreign institutions, and one for proposers from German institutions. Selected proposals from U.S. institutions will receive funding to support their data reduction and publication.

In addition to observing proposals there is also a call for new *SOFIA* new instrument proposals every couple of years or so. Although NASA will only fund U.S. based proposal development, instruments from other nations can be developed and flown on *SOFIA* on a no exchange of funds basis.

7. SYNERGIES WITH THE *AKARI* ARCHIVE

The observational capabilities of the AKRI and *SOFIA* instrument suites are quite complementary and the *AKARI* archive will serve as a rich source of targets for *SOFIA* follow-up. Figure 5 shows the wavelength coverage and point-source sensitivities of the *SOFIA* and *AKARI* instrumentation. The sensitivities are quite comparable, and follow-up observations can take advantage of the higher spatial resolution afforded by *SOFIA*'s large mirror as well as the higher spectral resolution for the brighter *AKARI* objects that are enabled by the high-resolution spectrometer instruments on *SOFIA*. As the *AKARI* survey is all-sky, it has objects visible from both Northern and Southern hemispheres, but as *SOFIA* can operate out of both any *AKARI* target can be seen by *SOFIA*.

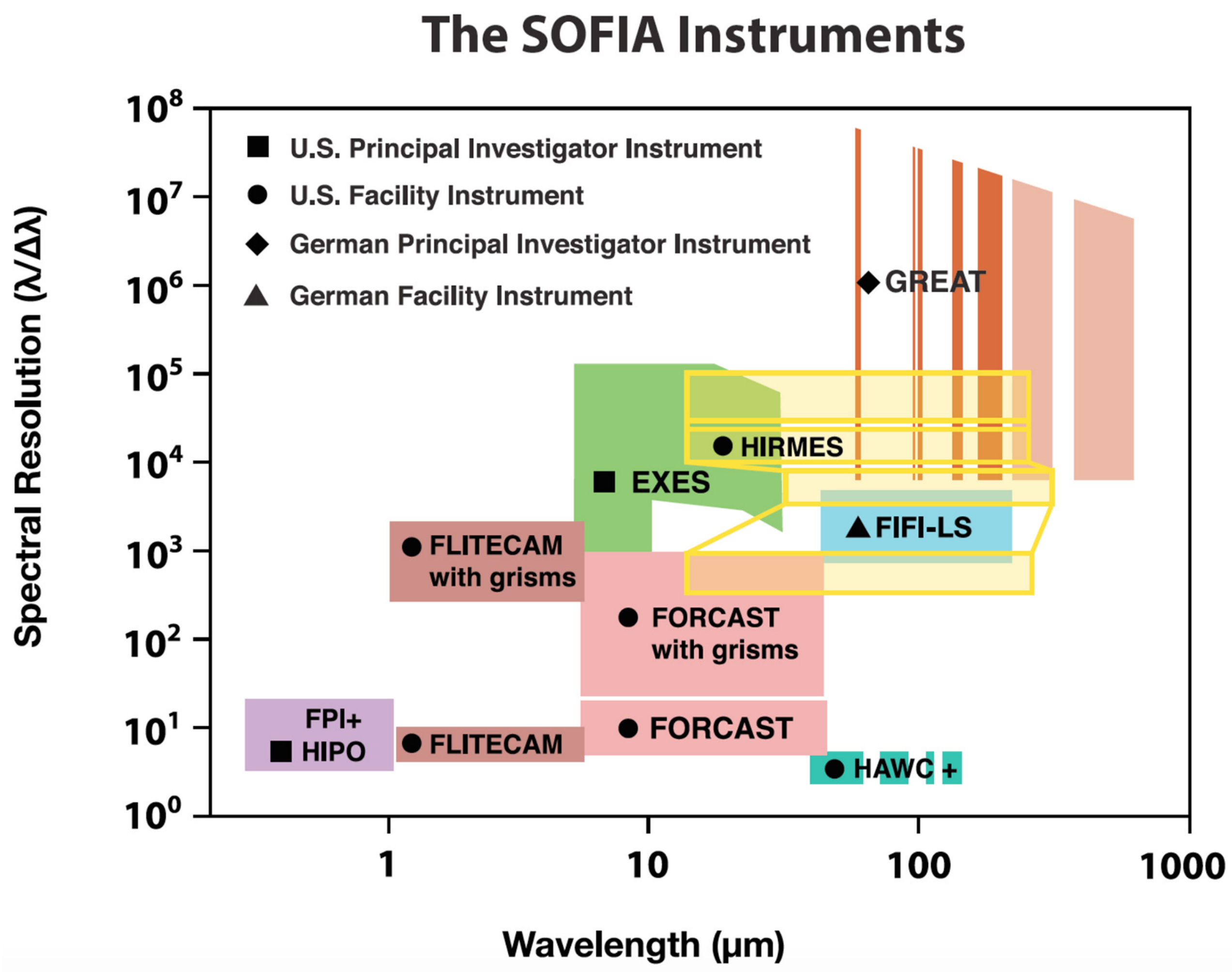

Figure 3. The wavelength and spectral resolution coverage of *SOFIA*'s instrument suite.

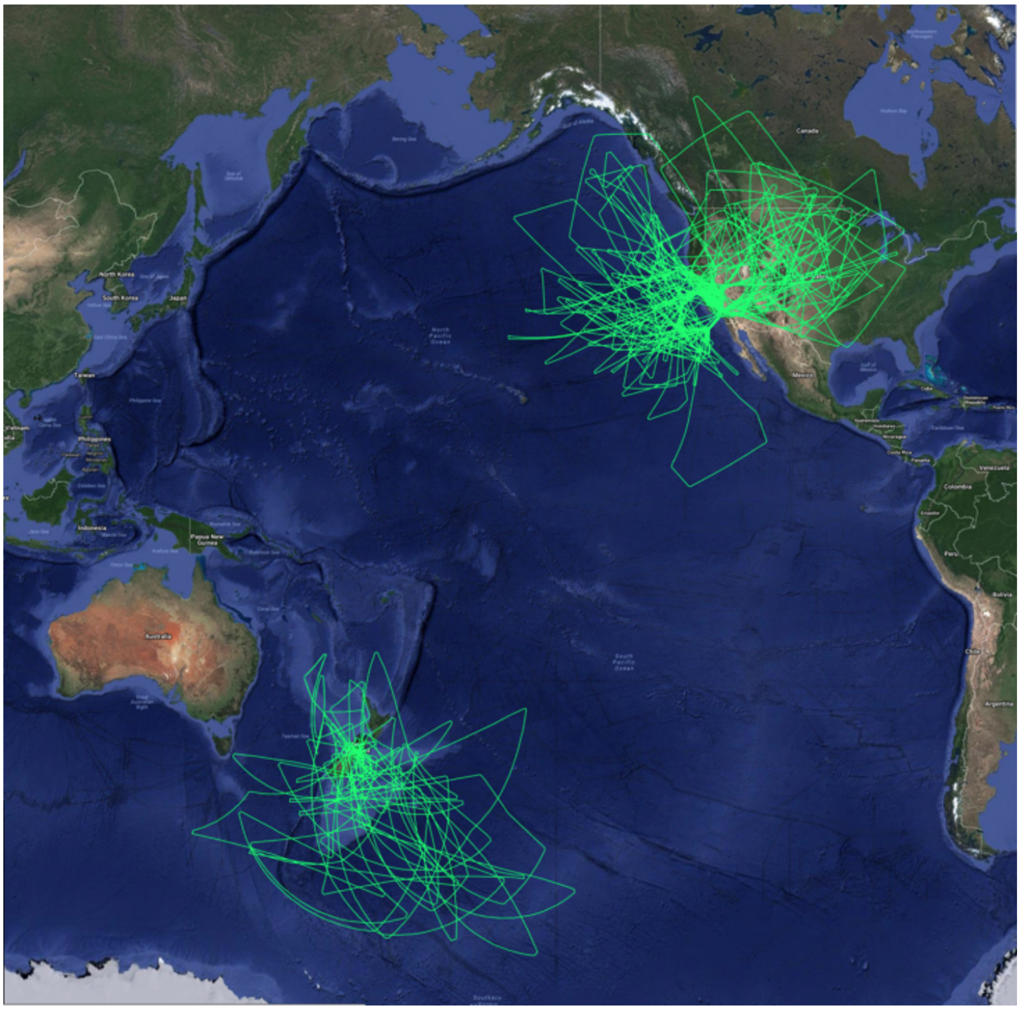

Figure 4. An overlay of the *SOFIA* flight paths for the year 2016. It can be seen that the flights form jagged closed paths originating at *SOFIA*'s Northern Hemisphere base in Palmdale, California, USA, and the Southern Hemisphere base in Christchurch, New Zealand.

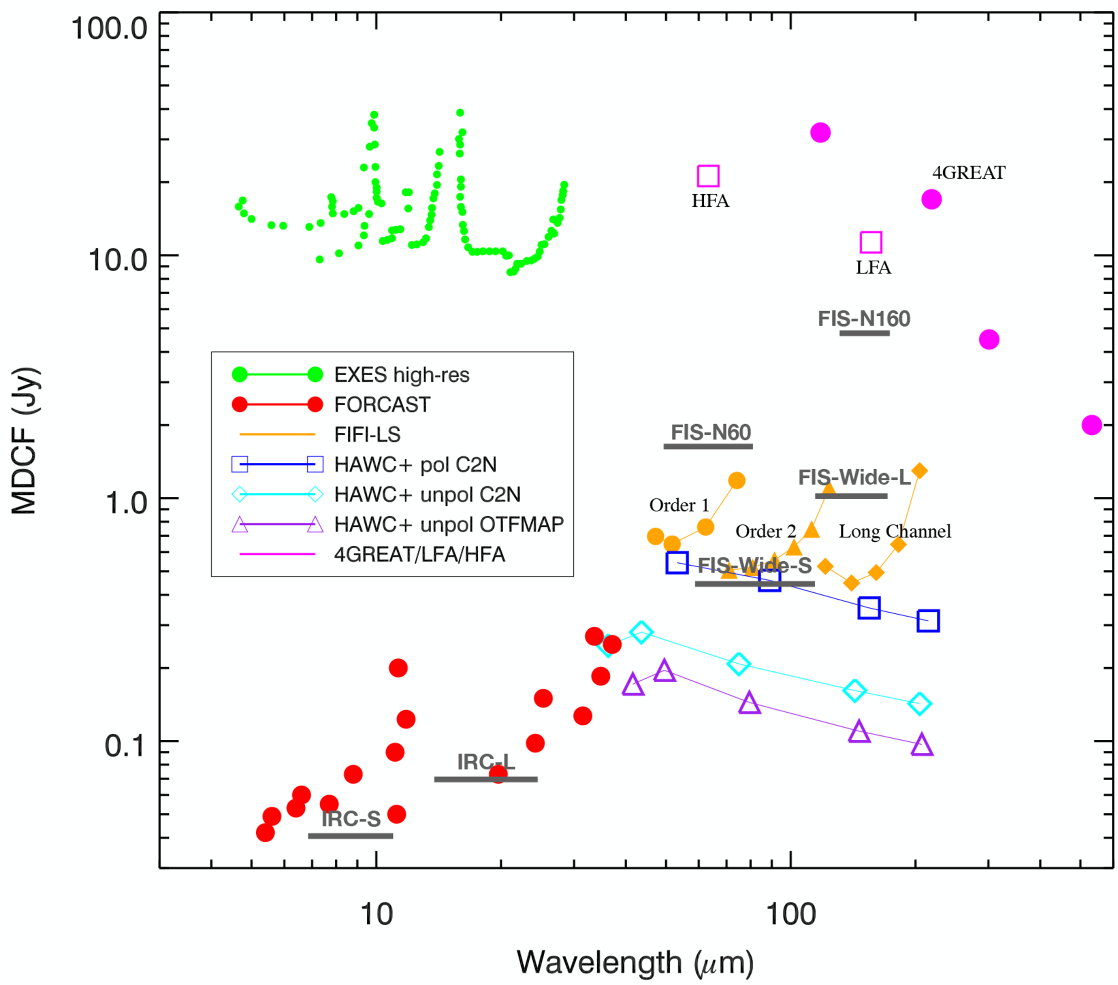

Figure 5. The point-source sensitivities of the *SOFIA* and *AKARI* instruments. The *SOFIA* instrument sensitivities are 5-σ limits in 15 minutes of integration time. The *SOFIA* instrument sensitivities are 4-σ limits from the IRC and FIS instrument catalogs (http://irsa.ipac.caltech.edu/data/AKARI/documentation/AKARI-FIS_BSC_V1_RN.pdf and http://irsa.ipac.caltech.edu/data/AKARI/documentation/AKARI-IRC_PSC_V1_RN.pdf).

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