

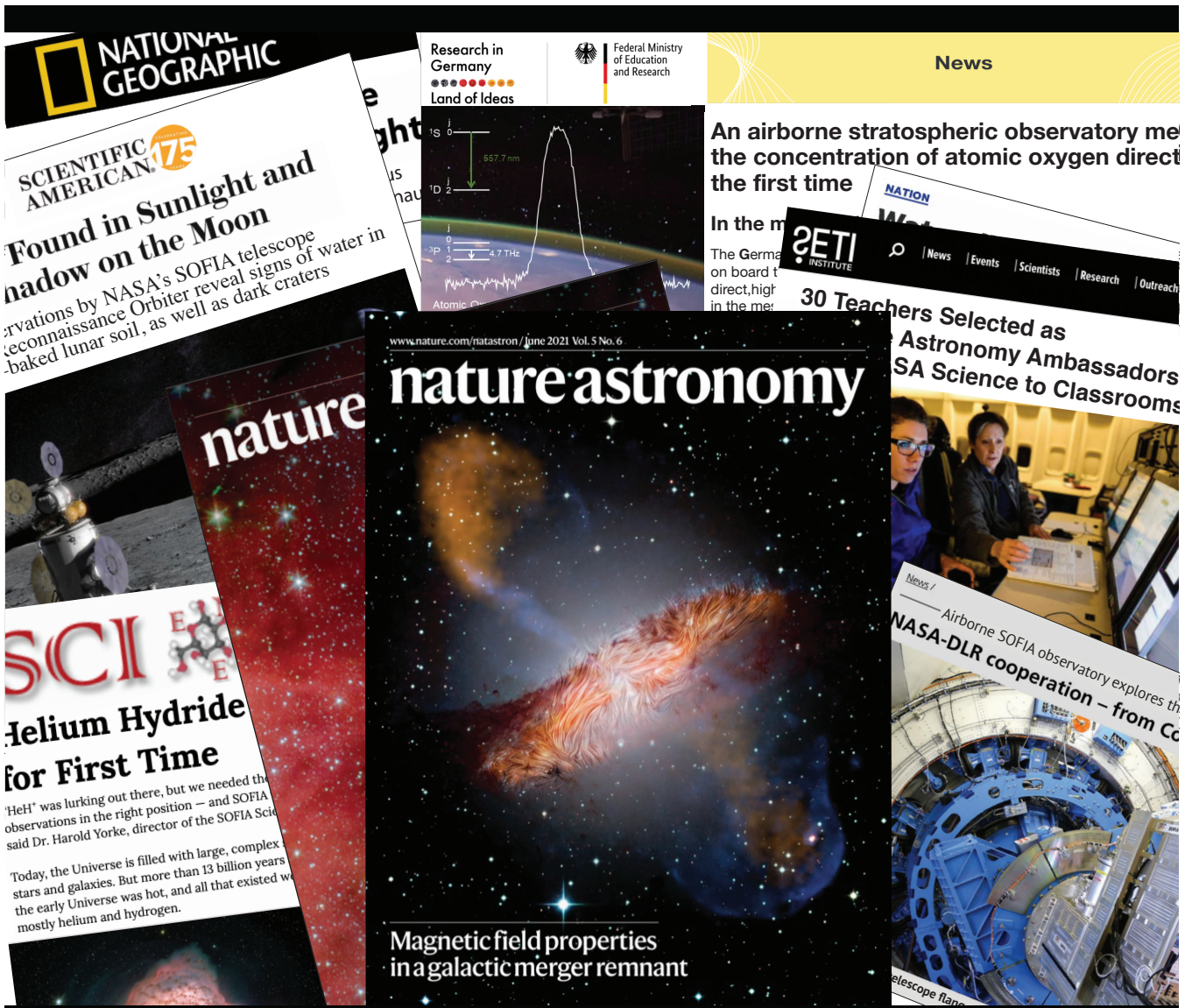


STATUS & FUTURE PROSPECTS



2022

Orion Nebula's magnetic fields superimposed on the evening sky as SOFIA prepares to observe the infrared universe.



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Aurora Image from SOFIA

This SOFIA Status and Future Prospects report
is based on information as of or before January 2022.

The content in this document was developed in preparation
for the 2022 Astrophysics Senior Review. Certain elements reflect language
that is written in a proposal style and respond to proposal requirements.

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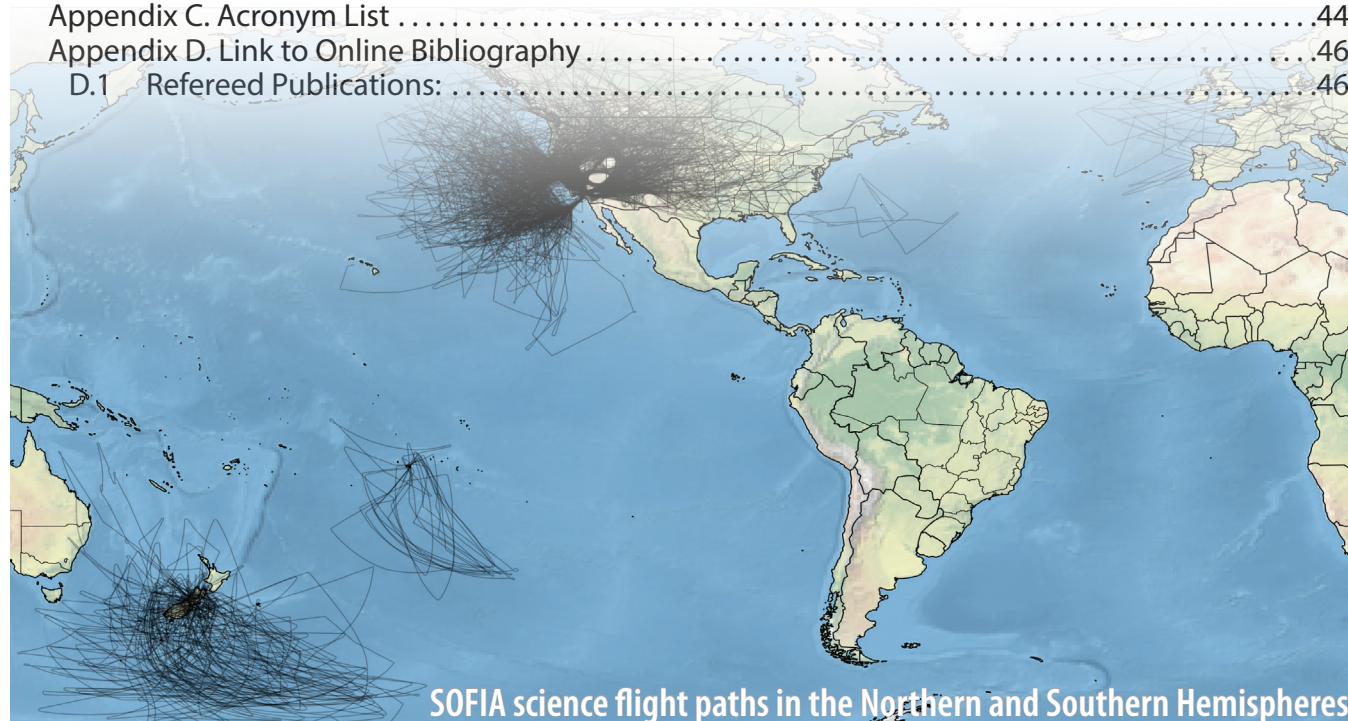
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EXECUTIVE SUMMARY

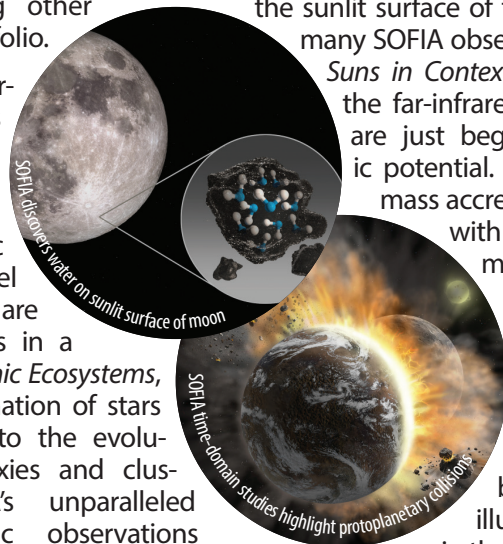
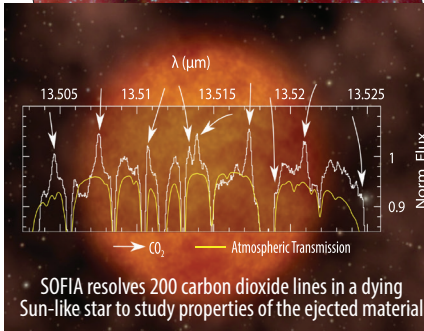
The Stratospheric Observatory for Infrared Astronomy (SOFIA) conducts a broad range of astrophysical and planetary science investigations using unique, state-of-the-art, mid- and far-infrared capabilities to address NASA's key astrophysics objectives and half of the science priorities of the 2020 Astrophysics Decadal Survey. SOFIA has also addressed all the recommendations of the 2019 Flagship Mission Review. The mission has increased scientific return, optimized operational efficiency, and reduced operating cost, thus enabling SOFIA to invest in new and improved instrumentation that will lead to new ground-breaking discoveries. This national asset is the only far-infrared facility offering guest observing opportunities to astronomers across the globe, thereby complementing other missions in the NASA astrophysics portfolio.

SOFIA's most recent capability, polarization mapping in the far-infrared, is revolutionizing the way scientists think about the role of magnetic fields. Such novel measurements are testing theories in a variety of *Cosmic Ecosystems*, from the formation of stars and planets to the evolution of galaxies and clusters. SOFIA's unparalleled spectroscopic observations make unambiguous detections of distinct molecular fingerprints and investigate complex physics across a wide array of astrophysical environments. These observations determine the molecular hydrogen fraction, constrain the turbulence in the interstellar medium, and measure the mechanical feedback from newly formed stars. Significant SOFIA contributions to interdisciplinary science include the first measurements of atomic



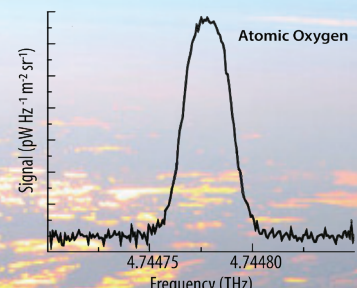
oxygen in the Earth's mesosphere and lower thermosphere (vital for atmospheric models and climate change predictions), as well as the recent discovery of water on the sunlit surface of the Moon. These are among the many SOFIA observations that address *Worlds and Suns in Context*. Time-domain observations in the far-infrared are so new that astronomers are just beginning to realize their scientific potential. SOFIA is already measuring the mass accretion rate in a variety of stars, and with its new multi-cycle observing mode, will play an important role in developing *New Messengers and New Physics*. SOFIA's unique science capabilities also provide compelling synergies with other observatories in NASA's portfolio. For example, studies of the bright, nearby Universe are key to illuminating the underlying physics in the more distant objects that will be targeted by the James Webb Space Telescope.

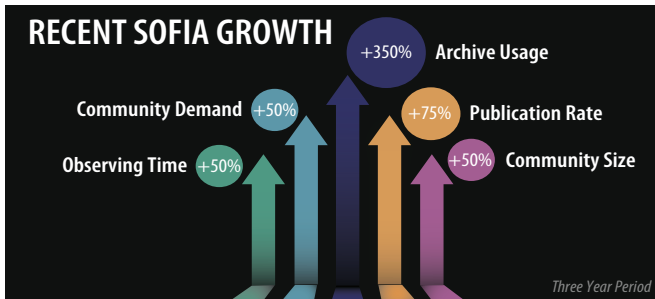
SOFIA's operational efficiency and scientific productivity are expanding, on a trajectory to achieve its full scientific potential. The annual publication rate has doubled in the last three years and the archiving of calibrated data is 50% faster. Archive upgrades have improved data accessibility and usability, resulting in increasing downloads by a factor of two. Over 90% of the data SOFIA collects are now taken under premium observing conditions. Oversubscription rates are 4 to 5 for observing time and archival funding. Legacy programs have increased to 30% of SOFIA's observing time, thereby significantly enriching the archive. Aggressive automation initiatives have improved accuracy and increased



SOFIA SCIENCE MAPS TO HALF OF THE 2020 ASTROPHYSICS DECADAL SURVEY'S SCIENCE PRIORITIES

SOFIA measurements of atomic oxygen in the Earth's atmosphere provide essential input for climate-change models





operational efficiency up to ten times in some observatory functions. A robust community outreach effort, including a standalone archival solicitation, increased grant funding, targeted workshops, and collaborations with other observatories, has increased SOFIA's visibility and appeal to a much wider audience of astronomers and planetary scientists. The SOFIA community has grown steadily to over 2000 investigators and authors, with 600 additional new-to-SOFIA astronomers added through science outreach events.

The prioritized mission objectives described in this document will ensure >50% growth in SOFIA's scientific return over the next three years. The proposed

during flights by proactively addressing reliability and obsolescence. The mission will start the process of transitioning to hybrid-remote operations, which can be a game changer for observatory operations and community engagement.

SOFIA exemplifies NASA's core values of diversity, inclusion, and teamwork in the mission's stewardship and operating model. As a crewed mission, SOFIA naturally fosters a culture of collaboration for mission success across and between disciplines, ranging from scientists and engineers to aviation and maintenance experts. Women make up half of the SOFIA leadership and support every aspect of the mission. Many of the recent observatory leadership positions and initiatives are designed to specifically support early-career scientists (e.g., the new far-infrared school) and students at minority-serving institutions (e.g., the new science and engineering internship program). The mission continues to capture the imagination of people around the world through public engagement activities in the US as well as during deployments abroad. SOFIA is inspiring the next generation of scientists and



SOFIA EXEMPLIFIES NASA'S CORE VALUES OF TEAMWORK, DIVERSITY, AND INCLUSION, INSPIRING AND PROVIDING OPPORTUNITIES TO THE NEXT GENERATION WORLDWIDE

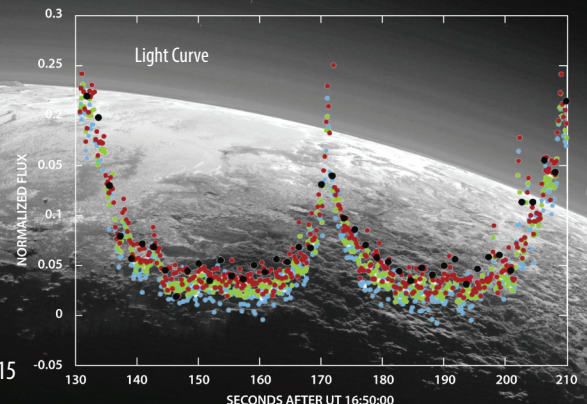
efforts will increase annual observing opportunities by 50% and double Southern Hemisphere observations. Investments in SOFIA instrumentation will not only keep SOFIA at the scientific forefront, but will also advance technology and prepare the community for the future far-infrared missions recommended by the 2020 Astrophysics Decadal Survey. New science outreach programs will grow and diversify SOFIA's user community, with particular attention to early-career scientists. SOFIA will prevent loss in science time

engineers through targeted activities, as demonstrated by recent joint outreach efforts with US consulates geared towards high school and university students, supporting and facilitating their passions in STEM.

SOFIA, a joint NASA (80%) and DLR (20%) mission, will continue to make bold and transformative changes that achieve scientific excellence, positively impact scientific communities, and empower the citizens of both nations and beyond.

SOFIA HAS UNDERGONE A TRANSFORMATION AND IS ON A TRAJECTORY TO ACHIEVE ITS FULL SCIENTIFIC POTENTIAL

Pluto Occultation: SOFIA and ground-based observations confirm haze in Pluto's Atmosphere June 29, 2015



1. INTRODUCTION

From the discovery of water on the sunlit surface of the Moon to the detection of the first molecule to form in the infant Universe, SOFIA explores a vast astronomical parameter space to reveal critical new information about our Solar System, our Galaxy, and beyond. Infrared emission is bright and widespread in practically all astrophysically interesting regions, and its light can be separated into polarizations and spread to form spectra. This enables SOFIA to investigate the role of magnetic fields from star formation to galactic super winds and the dominance of feedback from the Orion bubble to cold quasars. New instrumentation will allow SOFIA to address important new science, like measuring the mass of the molecular hydrogen and tracing the location of the snow line in proto-planetary disks.

Much of the radiant energy from planets, star-forming clouds, and galaxies emerges in the mid-infrared (mid-IR; 5-40 μm) and far-infrared (far-IR; 40-650 μm) (e.g., [Figure 1-1](#)), but water vapor in the Earth's atmosphere blocks mid-IR/far-IR at even the best terrestrial sites. By flying above 99.9% of the atmosphere's absorbing water, SOFIA can observe the infrared (IR) spectrum from ~ 1 to 1000 μm and tap into the wealth of astrophysical information accessible only at these wavelengths.

Recent SOFIA discoveries and future observing plans map directly to the priorities laid out in the 2020 Decadal Survey on Astronomy and Astrophysics (Astro2020) and the NASA SMD Science plan ([Table 1-1](#)). With its broad capabilities and access to over three orders of magnitude in wavelength, SOFIA enables a wide array of science and has published results that address over half of the Astro2020 questions (Column 1 of [Table 1-1](#)), many of which are described in the science case ([S2](#)). Unique mid-IR and far-IR measurements (Column 2) only possible with SOFIA instruments (Column 3) are currently being taken or planned for the future (Column 4). "How did we get here?" and *Cosmic Ecosystems* science dominate the SOFIA portfolio. "Are we alone?" and *Worlds and Suns in Context* are expanding domains of SOFIA science. SOFIA is poised to develop time-domain observations in the far-IR, which will address "How does the universe work?" and *New Messengers and New Physics*.

SOFIA's instrument suite exploits the full mid-IR/far-IR wavelength range with continuum imaging, high-resolution spectroscopy, and polarization mapping ([S3](#), [Figure 3-1](#)). Unlike space missions, SOFIA can repair, upgrade, and replace its instruments as science priorities evolve (e.g., new decadal science goals) and technologies improve. This continual development allows SOFIA to outperform and significantly extend the legacies of previous instruments, as well as prepare the groundwork for the future far-IR mission recommended by Astro2020. With community input, SOFIA has developed a roadmap ([S5](#)) to optimize the instrument suite

and enable new discoveries. Step 1 of that roadmap, upgrade of the HAWC+ instrument, has already begun.

SOFIA, a specially modified Boeing 747SP aircraft with a 2.7-m telescope, is the largest airborne observatory ever built. SOFIA is operated by an 80/20 partnership between NASA and DLR (German Aerospace Center), using contracts with Universities Space Research Association (USRA) and the Deutsches SOFIA Institut (DSI) to run their respective science centers ([S7](#)). Observing time and archival funding are available to the astronomical community through a competitive peer review process ([S3](#)). The Science and Mission Operations (SMO) center, located at NASA Ames Research Center (ARC), provides comprehensive support for SOFIA users ([S3](#)).

The SOFIA team has mastered the unique and complex operations of the observatory and works continuously to improve operational efficiency and scientific effectiveness. Neither space-based missions nor ground-based observatories are exact analogs, because SOFIA observations are tailored to the unique aspects and requirements of an airborne observatory ([S3](#) & [S6](#)). SOFIA is a crewed mission that employs an onboard team to fly the aircraft and operate the observatory ([S6](#)). SOFIA flight operations are based at NASA Armstrong Flight Research Center (AFRC). SOFIA deploys to southern sites to observe targets that are not accessible from the north.

Every aspect of the SOFIA mission has undergone a transformation in a short amount of time following the Flagship Mission Review (FMR) in 2019 ([S4](#)), with

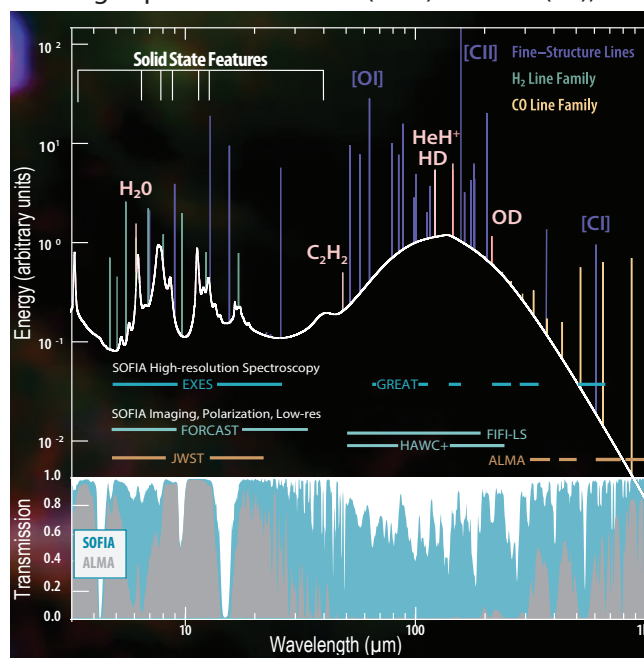


Figure 1-1 Top: The typical energy output of a star-forming galaxy illustrates that more than half of all energy output from galaxies is in the form of mid-to far-IR (5-500 μm). SOFIA instruments fill a critical spectral gap between JWST and ALMA, covering valuable diagnostic features in the form of infrared atomic and molecular emission lines and solid-state emission features. Bottom: Atmospheric transmission for SOFIA at 41,000 feet is far superior to even the driest, highest-altitude site on Earth, e.g., ALMA at 16,000 feet.

Table 1-1

SOFIA SCIENCE TRACEABILITY MATRIX

Decadal Science Questions †	Key Measurements	SOFIA Instruments	SOFIA Observations
◆ HOW DID WE GET HERE? COSMIC ECOSYSTEMS			
F-Q1: How do star-forming structures arise from, and interact with, the diffuse interstellar medium? §2.1.1, 2.1.3, 2.1.5	[C II] 158 μ m, [O I] 63 & 145 μ m, light hydrides, kinematics & Far-IR polarimetry	GREAT, FIFI-LS, HAWC+, *THzMap	FEEDBACK, HyGal, LMC+, GalMag, C+SQUAD
F-Q2: What regulates the structure and motions within molecular clouds? §2.1.2, 2.1.3, 5.6.2	[C II] 158 μ m, light hydrides, Far-IR polarimetry at 0.1 pc	HAWC+, GREAT, *THz-Map	SIMPLIFI, GalCen, HyGal
F-Q3: How does gas flow from parsec scales down to proto-stars and their disks? §2.1.2, 2.1.3, 2.3.1, 5.6.2	Far-IR polarimetry at 0.1 pc, Mid/Far-IR variability & high-res spectroscopy	HAWC+, EXES, GREAT, FORCAST, FIFI-LS, *DirectDet	FIELDMAPS, SIMPLIFI, HyGal
D-Q2: How do gas, metals, and dust flow into, through, and out of galaxies? §2.1.1, 2.1.3, 2.1.4, 5.6.2	[C II] 158 μ m, light hydrides, [O III] 88 μ m, Far-IR polarimetry <200 pc	GREAT, FIFI-LS, HAWC+, *THzMap, *DirectDet	HyGal, GalMag, LMC+
D-Q4: How do the histories of galaxies and their dark matter halos shape their observable properties? §2.1.5, 5.6.2	[C II] & [O III] in galaxies (< 200pc), [¹³ C II]	GREAT, FIFI-LS, *THzMap	M51, LMC+, Galaxies
◆ ARE WE ALONE? WORLDS AND SUNS IN CONTEXT			
E-Q3: How do habitable environments arise and evolve within the context of their planetary systems? §2.2.1, 2.2.2	6 μ m H ₂ O, [O I] 63 μ m, PH ₃ , D/H ratio from HDO	FORCAST, EXES, GREAT	Lunar, Europa, Earth, Venus, Comets
F-DA: Detecting and characterizing forming planets §2.2.2, 5.6.2	D/H ratio from HD	FORCAST, EXES, *DirectDet	Jupiter
E-Q2: What are the properties of individual planets, and which processes lead to planetary diversity? §2.2.1, 2.2.2, 5.6.2	R~10 ⁵ spectroscopy of H ₂ and organics, seasonal variation, occultations, high-speed (<0.1s) photometry, atmospheric haze evolution	FORCAST, EXES *DirectDet, FPI+,	Titan, Jupiter, Pluto, Triton
G-Q2: How does multiplicity affect the way a star lives and dies? §2.3.3	Mid/Far-IR photometric variations <i>Time Domain</i>	FORCAST, HAWC+	Stellar Mergers
G-Q3: What would stars look like if we could view them like we do the sun? §2.3.4	Mid/Far-IR photometry & spectroscopy, multi-epoch data <i>Time Domain</i>	FORCAST, FIFI-LS, GREAT, *DirectDet	Evolved Stars
E-Q1: What is the range of planetary system architectures and is the configuration of the Solar System common? §2.3.5	Mid-IR photometry variation <i>Time Domain</i>	FORCAST	Debris Disk
F-Q4: Is planet formation fast or slow? §5.6.2	HD 112 μ m velocity-resolved of proto-planetary disks for gas mass	*DirectDet	Proto-planetary Disks
◆ HOW DOES THE UNIVERSE WORK? NEW MESSENGERS AND NEW PHYSICS			
B-DA: Transforming our view of the Universe by combining new information from light, particles, and gravitational waves §2.3	Mid/Far-IR photometric variations <i>Time Domain</i>	FORCAST, EXES, HAWC+, FIFI-LS, GREAT	Supernovae
B-Q4: What seeds supermassive black holes and how do they grow? §2.1.4	Far-IR polarimetry, Mid-IR photometry, Far-IR R ~10 ⁶ spectroscopy	FORCAST, HAWC+, GREAT	Galactic Center
D-Q3: How do supermassive black holes form and how is their growth coupled to the evolution of their host galaxies?	Far-IR photometry	HAWC+	High-z Galaxies

†From Table 2.1, Table B.1 and Box F.1 of Astro2020 Report *THzMap and *DirectDet are potential future SOFIA instruments (§5.6) SOFIA Legacy Programs
◆ SMD Science Plan  Priority 1 Exploration and Scientific Discovery

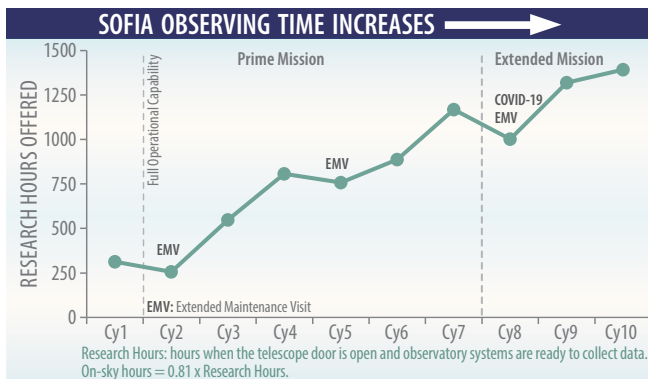


Figure 1-2. SOFIA observing time offered to the community has increased consistently, providing 50% more time in the extended mission. creative adaptations implemented to maximize scientific return during the early stages of the COVID-19 pandemic (§6.7 & §7.3). Through this transformation, SOFIA can now provide 50% more observing time to the community (Figure 1-2), with twice as many flights in the Southern Hemisphere. SOFIA’s prioritized mission objectives (§5) will significantly enhance its scientific return, achieving over a factor of two increase in its publication rate. SOFIA’s outreach to the US and worldwide communities will continue to grow, with a special focus on creating opportunities for early-career scientists and engineers from underrepresented groups and minority-serving institutions (§7, Figure 7-2).

SCIENCE AND IMPLEMENTATION

2. SCIENCE

2.1 Cosmic Ecosystems

2.1.1 Star-Formation and Feedback

How does injection of energy, momentum, and metals from stars (“stellar feedback”) drive the circulation of matter between phases of the ISM and CGM? (F-Q1c¹)

Feedback of energy into the interstellar medium (ISM) from the star-formation process is now recognized as a key element in the life cycle of galaxies. Probing local stellar feedback not only elucidates the ecology of the Milky Way but also calibrates the powerful feedback effects experienced by galaxies at high redshifts with much higher star-formation rates ($\sim 100 M_{\odot}/\text{yr}$). Spitzer’s large-scale surveys reveal that the galactic plane is permeated by bubbles with a wide range of sizes and shapes that are driven by radiative and mechanical energy output from stars. The expansion of these bubbles is an indicator of the energy involved, but high-resolution spectroscopy provided by GREAT is required to resolve their velocities.

¹ F-Q1c is a sub-question of primary question F-Q1 [Appendix F; Astro2020 report] as stated in Table 1-1. The Science §2 lists these relevant sub-questions from various Astro2020 appendices to show traceability to SOFIA science.

Gas in star-forming regions illuminated by young stars is ideally suited for mapping in the [CII] 158 μm far-IR fine-structure line. Like H α in the optical, CO (2-1) in the millimeter, and hydrogen $\lambda 21\text{-cm}$ in the radio, [CII] is the workhorse line in the IR. It is the dominant cooling line for gas illuminated by the ultraviolet radiation field from nearby massive stars. Thus, [CII] directly probes the radiative and mechanical interactions that govern the complex processes of star formation.

GREAT has produced the first velocity-resolved, ~ 1 square degree [CII] map of Orion (C+SQUAD program). Theoretical models suggest that ionization drives the dissolution of molecular clouds, but the SOFIA [CII] Orion survey revealed much higher expansion velocities (~ 13 km/s) and masses ($\sim 1500 M_{\odot}$) for the expanding shell than these models predict. Indeed, the stellar wind from θ^1 Ori C dominates the feedback and will disrupt its molecular cloud long before the star goes supernova [Pabst et al 2019; 2021]. CO data reveal several small (0.05 pc) globules along the edges of the bubble, possibly representing preexisting density enhancements that were compressed by the wind-driven expansion. The net effect of feedback may be both destructive (dispersing the cloud) and productive (triggering new star formation as the bubble interacts with the surrounding material) [Pabst et al. 2020].

The FEEDBACK Legacy Program extends the Orion survey to 11 regions covering a wide range of stellar and environment characteristics, from single OB stars to super star clusters [Schneider et al. 2020]. This program (now 70% complete) can determine if these results are unique to Orion or apply more broadly to the galactic ecosystem. The data will quantitatively assess the energy and momentum input by massive stars and determine if feedback promotes or hinders star formation. Early results from the RCW 120 region (Figure 2-1) show compelling evidence of triggered star formation where the strong shock appears to have compressed pre-existing density fluctuations that collapsed to form protostars [Luisi et al 2021].

2.1.2 Magnetic Fields in Star-Formation

How do Dense Molecular Cloud Cores Collapse to Form Protostars and their Disks? (F-Q3a)

Molecular clouds resist free-fall gravitational collapse, making star formation slow and inefficient. Magnetic fields and turbulence can both hinder the process, but their relative importance remains unclear. While the magnetized ISM has been studied using polarization, the presence of synchrotron emission and extinction make it difficult to observe dusty star-forming regions in most wavebands. Because thermal dust emission typically peaks at $\sim 100 \mu\text{m}$, the most effective probe of magnetic fields is via polarization at far-IR wavelengths. This polarized signal measured by HAWC+ can be used

to image the direction of magnetic fields on the critical subparsec-to-parsec scales of cores and filaments where stars are born. Using the Davis-Chandrasekhar-Fermi method, SOFIA now routinely measures magnetic field strengths of 0.1 to 2 mG in a variety of astrophysical environments [e.g., Chuss et al. 2019, Pillai et al. 2020, Zelinski et al. 2021, Guerra et al. 2021].

At the scales of dense cores where individual stars are formed, theory predicts that charged particles can flow initially only along the field lines. Later, the gravitational pull grows strong enough to pinch the field lines, giving rise to a characteristic hourglass shape. Observations of such features are rare and have been limited to high-mass stars. SOFIA made the first detection of the hourglass feature (Figure 2-2) in a low-mass, Sun-like protostar [Redaelli et al. 2019]. Similar hourglass features have now been observed by SOFIA on larger (1-100 pc) scales in the Orion star-forming region and the 30 Doradus super star cluster, more than 10 and 1000 times larger than the dense cores, respectively.

What Is the Origin and Prevalence of High-Density Structures in Molecular Clouds and What Role Do They Play in Star-Formation? (F-Q2b)

Stars form predominantly in cold, dense, and extremely filamentary clouds. Planck observations revealed that matter flows in the direction of the magnetic field in low-density outskirts of these filaments and perpendicular to the direction of the field in the dense central regions [Planck XXXV 2016]. L1688, part of the Rho Ophiuchus cloud complex, is the closest site of clustered star formation to the Sun. The Planck and SOFIA observations together cover scales ranging from 3 pc (the size of L1688) down to 0.02 pc. While the Planck data for Ophiuchus suggest a transition in this region,

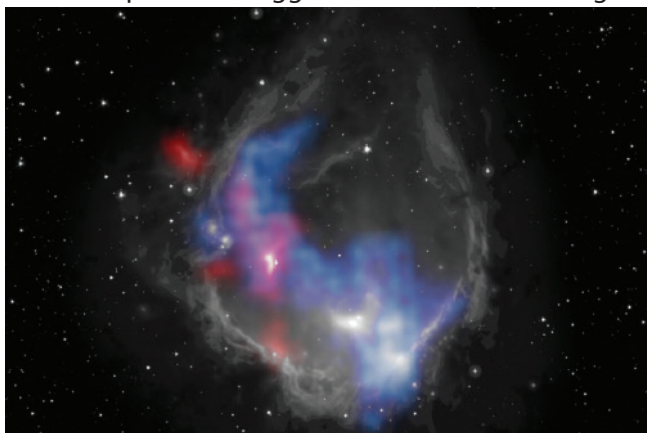


Figure 2-1 Composite image of RCW 120 with bubble-shaped clouds detected by the *Spitzer*. SOFIA [CII] emission shows faster-than-expected expansion toward us (blue) and away from us (red), triggering the birth of stellar neighbors and demonstrating for the first time that feedback can operate on very short timescales.

SOFIA DISCOVERED THAT STELLAR WINDS, NOT SUPERNOVAE, DISPERSE MOLECULAR CLOUDS, TRIGGER THE BIRTH OF NEW STARS, AND CAN DOMINATE FEEDBACK.

SOFIA, with 60 times higher angular resolution, provides conclusive evidence. SOFIA discovered that the large-scale magnetic field in L1688 has an energy density comparable to or greater than that of turbulent gas motions [Lee et al. 2021].

Magnetic fields play an important role in shaping these filaments, but for stars to form, dense cores need to collapse. The extreme youth and proximity of the Serpens South Cluster, which sits at the center of a network of dense filaments, make it an ideal laboratory for testing the role of magnetic fields in an early stage of star formation. In the most opaque parts of the Serpens filaments, the magnetic field once again becomes parallel to the flow of gas, allowing gravitational collapse to occur even in the presence of relatively strong magnetic fields [Pillai et al. 2020].

With only a handful of robust measurements available, the study of magnetic fields in dense filaments at parsec scales is in its infancy. SOFIA has begun two Legacy programs: FIELDMAPS images the largest filaments to determine their magnetic topology, and SIMPLIFI images smaller-scale filaments where individual star-forming cores can be resolved. These high-quality polarization measurements for collapsing clouds will provide crucial observational constraints of magnetic field models and calculations.

2.1.3 Composition and Evolution of the ISM

Understanding how primordial gas evolves into galaxies, stars, and planets remains one of the most important goals of modern astrophysics. When temperatures in the early Universe fell below ~4,000 K, the light elements produced in the Big Bang began to combine. Traces of ionized hydrogen reacting with neutral helium created the Universe's first molecular bond,

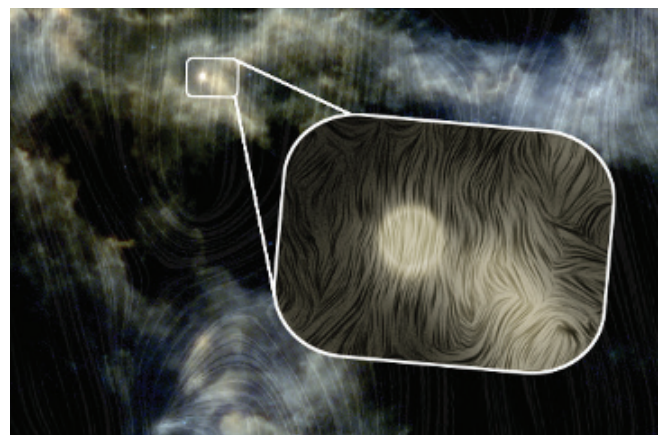


Figure 2-2 A portion of the Lupus I cloud complex observed by *Herschel*. Streamlines show the associated magnetic fields based on Planck polarization data. The inset shows a HAWC+ total intensity image of the low-mass protostellar core and HAWC+ streamlines showing the magnetic fields are beginning to take on the expected hourglass shape.

HeH⁺. Destruction of the HeH⁺ bond provided a pathway to form molecular hydrogen and thereby influenced the structure of the early Universe by providing a dominant mechanism to cool gas and form stars. Despite its importance to Big Bang chemistry, observations of this molecule in space have eluded detection until GREAT discovered modern helium hydride in the PDR of a planetary nebula, NGC 7027, where the radiation field produced by the central white dwarf combined with a high density of hydrogen and helium provided the perfect formation conditions for this molecule [Guesten et al. 2019].

How do Molecular Clouds Form from, and Interact with, their Environment? (F-Q1b)

Although CO is typically used as the fundamental probe of molecular gas, about half of the molecular material in the Galaxy is CO-dark. GREAT has measured molecular column density using the CH radical [Wiesemeyer et al. 2018], which can trace molecular gas over several orders of magnitude in column density without saturation. Jacob et al. [2020] have extended the utility of CH to even higher column density gas using ¹³CH (Figure 2-3). An accurate inventory of molecular gas is crucial to a more detailed understanding of the star formation process, and these CH radical measurements can provide a more complete tracing of molecular gas than CO.

Astrochemistry of the simplest molecules, light hydrides, probes the evolution and composition of the ISM. These light hydrides have their ground-state rotational transitions in the far-IR. The HyGAL Legacy program will provide an unprecedented assessment

SOFIA DETERMINES THE ROLE MAGNETIC FIELDS PLAY IN THE COMPLEX PROCESSES OF STAR-FORMATION.

of light hydride abundances in a wide variety of Galactic environments. It will quantify the abundance of H₂ in CO-dark clouds; measure abundances of OH⁺, H₂O⁺, ArH⁺, SH, OH, and CH toward 22 Galactic sources; and supply critical constraints for chemical reaction networks.

Light hydrides whose chemistry is initiated by cosmic ray ionizations (H₂O⁺, OH⁺, and ArH⁺) can determine the cosmic ray rate. Other light hydrides, which require warm gas heated by shocks for their formation (CH and SH), characterize turbulence and its dissipation in the diffuse ISM.

How do Protostars Accrete from Envelopes and Disks, and What does this Imply for Protoplanetary Disk Transport and Structure? (F-Q3b)

High-resolution molecular line surveys provide a chemical inventory for star-forming regions – essential for establishing the relative importance of potential chemical networks, understanding organic chemistry associated with star formation, and linking the organic inventory of nascent Earth-like planets to that of the various protoplanetary reservoirs available. Many simple molecules do not have allowed pure rotational transitions (e.g., CH₄, C₂H₂) or are obscured by telluric absorption (e.g., H₂O) and cannot be observed at sub-mm wavelengths. The first comprehensive high-resolution molecular line survey with EXES is opening up a largely unexplored discovery space [e.g., Nickerson et al. 2021, Barr et al. 2020]. The hot core in Orion is a rich source of chemistry and known to harbor a variety of molecules. Observation of the forest of molecular transitions in this wavelength region not only creates a rich legacy archive, but also provides a valuable reference

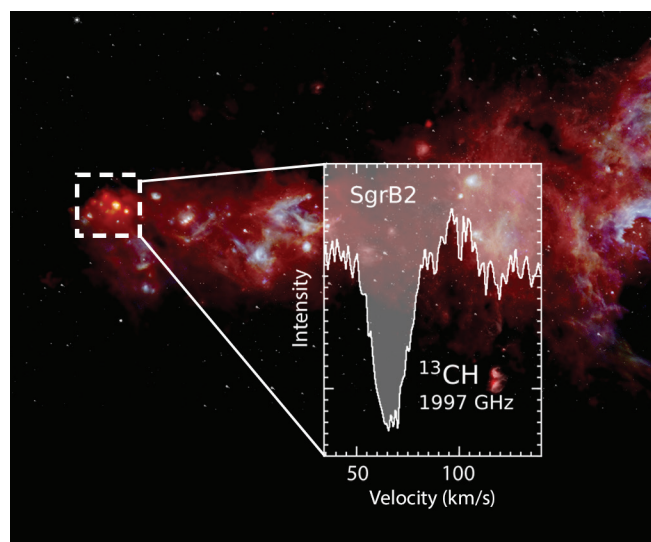


Figure 2-3 The first detection of ¹³CH in the interstellar medium. SOFIA absorption spectrum of ¹³CH corresponding rotational transition near 2 THz in the direction of SgrB2(M) superposed over a composite infrared image of the Sgr B complex.

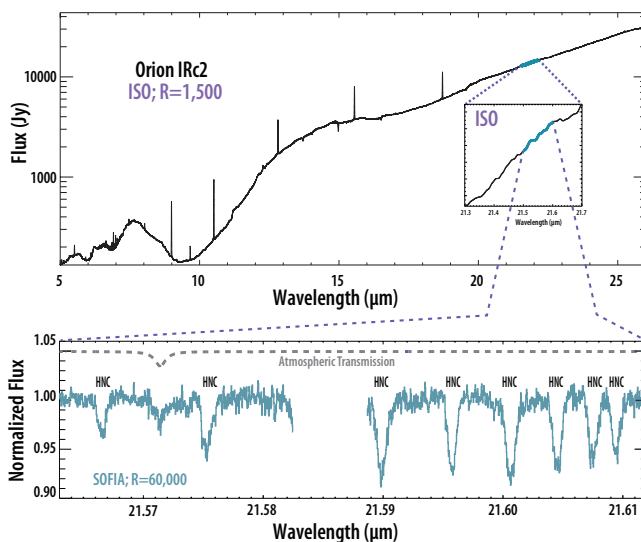


Figure 2-4 (Top) ISO spectrum with comparable spectral resolution (R~1500) of JWST/MIRI. (Bottom) With its much higher spectral resolution (R~60,000) SOFIA can detect many ro-vibrational lines of HNC, which will be indiscernible from the continuum of JWST's lower spectral resolution.

database for JWST. While JWST will be able to probe weak absorptions in faint continuum sources, such as disks around low-mass protostars, it lacks the spectral resolution to separate individual transitions (Figure 2-4).

2.1.4 Magnetic Fields in Galaxies

The production, distribution, and cycling of metals. (D-Q2b)

The coupling of small-scale energetic feedback processes to the larger gaseous reservoir. (D-Q2c)

Magnetic fields arise in the infant Universe from inhomogeneities and anisotropies of electric charge. Theory suggests that the amplification of this "seed" field via, e.g., galaxy formation, mergers, accretion flows, and supernovae explosions, as well as the feedback associated with these processes, is required to produce the field we observe today. Recent SOFIA results find that the magnetic fields are strong enough to regulate star formation, affect the global kinematics of the gas, and even modify the rotation curves of galaxies. Understanding of the origin, amplification, and morphology of the magnetic field is crucial to forming a complete picture of galaxy development.

HAWC+ measured, for the first time, the magnetic field tracing the spiral arms of NGC 1068 and confirmed a prediction of the density wave theory. Under this scenario, the spiral arms should look slightly different for several tracers because they appear at distinct phases of the density wave. The spiral pattern is traced by existing stars in the optical, the inter-arm diffuse medium in the radio, and ongoing star formation in the far-IR, the component seen by SOFIA [Lopez-Rodriguez et al. 2020]. HAWC+ also investigated the large-scale transfer of matter from the body of the host galaxy to the active nucleus and discovered that magnetically driven flows feed the super massive black hole at the center of NGC 1097 [Lopez-Rodriguez et al. 2021a]. HAWC+ observations of the merger galaxy, Cen A, show that the magnetic field orientation is tightly aligned with the warped molecular disk (Inside cover art). Although magnetic fields were key to shaping the early Universe, they were originally weak and needed to grow stronger over time, and galactic mergers appear to be one of the strengthening mechanisms [Lopez-Rodriguez et al. 2021b].

Observations of M82 reveal a bipolar superwind that originates in the core and extends out into the halo and beyond. Early observations from HAWC+ show that the geometry of the magnetic field at the base of the superwind is perpendicular to the plane of the galaxy, consistent with a scenario where the outflow is dragging the field along with it. Lopez-Rodriguez et al. [2021c] used a well-tested technique borrowed from heliophysics – the potential field extrapolation

UNDERSTANDING OF THE ORIGIN, AMPLIFICATION, AND MORPHOLOGY OF THE MAGNETIC FIELD IS CRUCIAL TO FORMING A COMPLETE PICTURE OF GALAXY DEVELOPMENT.

– to determine that these magnetic field lines extend forever, channeling matter enriched with elements like carbon and oxygen into intergalactic space and magnetizing the intergalactic medium (Figure 2-5).

In an emerging field where every observation leads to new discoveries,

a Legacy program surveying a diverse array of nearby galaxies is under way. Its results will help astronomers piece together a coherent picture of how magnetic fields amplified by turbulent gas motions arising from galactic outflows, mergers, and active galaxies have evolved over cosmic time, especially during the violent, feedback-dominated early Universe.

2.1.5 [CII] as a Tracer of Star-Formation

Connecting local galaxies to higher redshift galaxies. (D-Q4c)

The cosmic cycle of star formation is an essential part of the evolution of the Universe, and the far-IR fine-structure line [CII] at 158 μm is one of the important tracers of star-forming activity [e.g., de Looze et al 2014; Herrera-Camus et al 2015]. Observations of [CII] have become more important recently because the cosmological redshift moves the line from distant galaxies into the band detectable by ALMA even out to redshift of 6. Studies of early galaxies use the strength of this spectral line as a direct indicator of the star-formation rate (SFR) in those galaxies that appear only as a point source. [CII] observations in the nearby Universe are critical to understanding the origin of the emission and what it reveals about galaxy evolution.

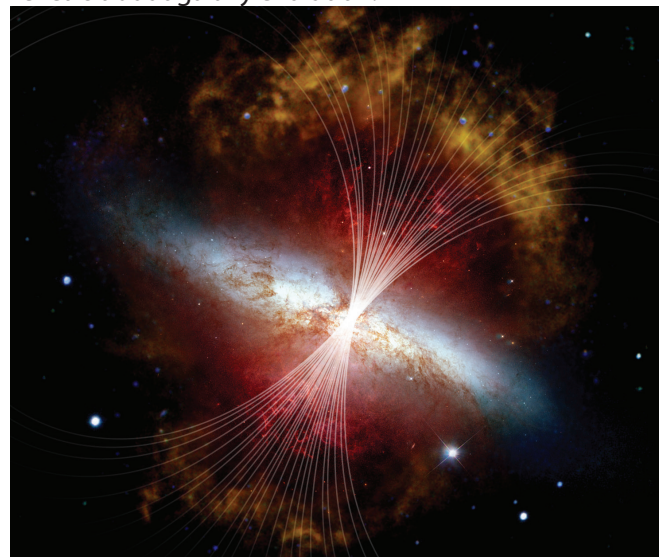


Figure 2-5 The Magnetic field in the M82 superwind: Researchers used HAWC+ polarization data and tools that have been utilized extensively to study the physics around the Sun to extrapolate the potential magnetic field strength and structure up to 10 kpc around the galaxy. The field lines appear to extend indefinitely into intergalactic space, like the Sun's solar wind, creating magnetic highways that channel star-processed matter beyond the starburst core.

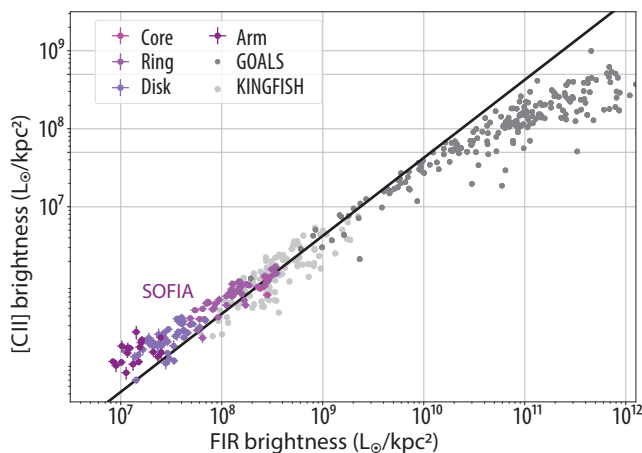


Figure 2-6 The [CII] surface brightness versus the Far-IR surface brightness for diverse regions in nearby galaxies (e.g., NGC 7331) and for integrated light of galaxies from the KINGFISH and GOALS surveys.

Spatially resolved FIFI-LS maps of [CII] separate star-forming regions and spiral arms, demonstrating that [CII] is a star-formation tracer [Bigiel et al. 2020], but detailed studies of nearby galaxies (e.g., NGC 7331, Figure 2-6) show systematic deviations [Sutter et al. 2021]. If [CII] and far-IR surface brightnesses were both linearly dependent on SFR, the points in Figure 2-6 would fall along the line. The departure on the right shows the well-known “[CII] deficit” for the brightest IR galaxies. The departure on the left, however, is revealed only because FIFI-LS can separate nearby galaxies into diverse regions, some of which have significant cold and CO-dark gas.

GREAT observations of two representative local spiral galaxies, M101 and NGC 6946, found that the molecular and atomic phases of the ISM contribute about equally to the total [CII] emission. This is very different from the results of Milky Way regions where the atomic gas contributes <15% to the [CII] emission [Tarantino et al. 2021]. This difference suggests that the spatial scale of a measurement has a profound effect on the multi-phase nature of [CII] emission. At larger scales (including the integrated flux of a galaxy), more diffuse gas is averaged together with star-forming regions, producing a substantial component of [CII] associated with the atomic gas.

FIFI-LS observations also reveal bright [CII] emission that is not associated with star formation. In particular, Smirnova-Pinchukova et al. [2019] found a galaxy ten times more luminous in [CII] than other galaxies with comparable total IR luminosity. The excess [CII] emission arises from a large-scale shock associated with the galaxy’s central radio jet plowing into the disk. A similar result was found for the barred spiral galaxy NGC 7479 [Fadda et al. 2021].

In addition, recent SOFIA observations have revealed several cases of optically thick [CII] emission from nearby star-forming regions [Okada et al. 2019;

Guevara et al. 2020]. The structured line profiles and high optical depth visible in the bright sources of strong [CII] emission revealed substantially higher [CII] column densities than those estimated using an optically thin approximation. Therefore, physical parameters derived from the optically thin approximation need to be treated with caution.

The [CII] measured using ALMA for high-redshift galaxies and interpreted in terms of SFR relies on calibration using nearby galaxies that SOFIA alone can obtain. In the next three years, SOFIA will observe a large array of nearby galaxies to calibrate [CII] as a star-formation tracer. Moreover, FIFI-LS will map [CII] and [OIII] emission in the most prominent large-scale star-forming molecular cloud complex in the Large Magellanic Cloud (LMC). [CII] will probe CO-dark molecular gas (expected to be 10 times more prevalent in the LMC), and [OIII] will probe ionized gas. These measurements are critical to understanding how star formation differs in low-metallicity systems – the best analogs for galaxies in the early Universe.

2.2 Worlds and Suns in Context

2.2.1 Solar System: Measurements of Habitability

What processes influence the habitability of environments? (E-Q3b)

Habitability of a planet (at least by known types of lifeforms) derives not only from its surface temperature but also, critically, from the presence of water and organic material on the surface. Earth formed hot and, apart from water upwelled via volcanism, should have been devolatilized and dry after formation. The origin of the Earth’s water and organics is one of the most tantalizing problems of science, with a likely exogenic origin from comet and asteroid impacts or interplanetary dust from comet and asteroid debris [Daly et al. 2021]. SOFIA addresses this topic through measurements of water on the Moon as well as water and carbonaceous material in comets. SOFIA is also capable of measurements of water on primitive asteroids, which will improve our understanding of the distribution of water in the early Solar System.

Lunar Water: SOFIA made the first-ever detection of the water molecule on the sunlit surface of the Moon [Honniball et al. 2021]. This discovery refines our understanding of the behavior of water and how volatile elements survive on airless bodies throughout the Solar System and beyond. Water and other volatiles can influence the internal processes and surface expression of planets. Water suppresses the melting point of rock, promoting volcanism, and reduces the viscosity of planetary interiors, enabling more efficient internal circulation and heat transfer.

The unambiguous water detection was made possible by SOFIA’s unique capabilities and the sensitivity

of the FORCAST spectrometer. The fundamental bending vibration of the H-O-H molecular bond occurs at 6.1 μm , which is specific to water and does not suffer blending from other OH-related compounds. Although the Moon's surface is very dry, 100 times drier than sand in the Sahara Desert, the presence of surface water in the detected amounts is puzzling. The authors speculate that much of the water is trapped in impact glasses, or within or between grains sheltered from sunlight.

SOFIA has initiated a Legacy program to shed more light on the formation, retention, and transport of water across the lunar surface. Plans include mapping the water across polar regions, at selected areas across the lunar surface, and at different lunar times of day. These observations will provide synergies with and support of future NASA missions, including the VIPER lunar rover that will explore the Moon's South Pole and the Artemis program that will return humans to the Moon. Unlike the Earth, the Moon has no erosion to erase the history of comet and asteroid impacts, and therefore a map of lunar water abundance will also provide deeper insight into the late heavy bombardment of the inner Solar System and quantify its influence on Earth's habitability.

Comets: Oort Cloud comets spend most of their lifetime far from the Sun and contain the most pristine and unprocessed material in the Solar System. Woodward et al. [2021] analyzed the FORCAST mid-IR spectrum of the Oort Cloud comet Catalina (C/2013 US10), finding its dust population to be dominated by amorphous carbon mixed with a smaller amount of amorphous silicate grains. This C/Si ratio (Figure 2-7) is similar to that of the Sun, the ISM, and other dynamically new comets observed with SOFIA, but much higher than that found in the Earth, meteorites, or interplanetary dust. A gradient in the C/Si ratio from the inner to outer Solar System suggests that the outer protoplanetary disk was much richer in carbon than the inner disk; therefore, comets ejected to the Oort cloud by giant-planet formation deliver net positive amounts of carbon to the terrestrial planets, potentially contributing a late veneer of organics to the Earth's biosphere.

Using GREAT observations of deuterated water, Lis et al. [2019] determined a D/H ratio in comet 46P/Wirtanen that is the same as in the Earth's oceans (Figure 2-7). The relatively high deuterium content of Earth's oceans relative to the protosolar nebula can occur when water is formed at low temperatures (10-20 K) found in the outer Solar System. This result supports the prevailing theory that water was delivered to the early Earth via impacts by bodies like comets that formed beyond the snow line.

SOFIA MEASURES
ATMOSPHERIC
PROPERTIES OF PLANETS
AND MOONS THAT
ARE IMPOSSIBLE FROM
THE GROUND AND
PROVIDE CRITICAL
COMPLEMENTARY DATA
FOR NASA SMD MISSIONS
(CASSINI, NEW HORIZONS,
VIPER, ARTEMIS).

SOFIA will continue to measure water, D/H, and C/Si by observing the brightest comets entering the inner Solar System. New comets will be discovered more routinely when the Vera Rubin Observatory begins its Large Synoptic Survey of Space and Time (LSST) at the end of 2023. Although spectacular comets like C/1995 O1 (Hale Bopp) are rare, the resulting high signal-to-noise spectroscopy of faint, deuterated molecules holds critical clues to the volatile record and thereby the origin of the life on Earth.

Venus: SOFIA observed Venus in late 2021 to confirm or refute the widely publicized detection by ground-based telescopes of phosphine in that planet's atmosphere [Cordiner et al. in prep]. Phosphine is difficult to synthesize and is rapidly destroyed in the conditions found in the Venusian atmosphere, so its presence would signal unknown geochemical, photochemical, or even biological processes. The detection remains controversial [Encrenaz et al. 2020, Snellen et al. 2020, Akins et al. 2020]. SOFIA can measure high-dipole-moment rotational transitions that are two orders of magnitude more sensitive to PH₃ abundance than the claimed abundance based on ALMA data [Greaves et al. 2020], allowing SOFIA to settle the issue of whether the potentially biogenic PH₃ is present in the atmosphere of Venus.

2.2.2 Solar System: Atmospheres of Planets and Moons

How does a planet's interaction with its host star and planetary system influence its atmospheric properties over all time scales? (E-Q2d)

Earth: Atomic oxygen, an important player in climate-change models, has been measured directly for the first time in one of the least understood regions of Earth's upper atmosphere, which includes the mesosphere and lower thermosphere [Richter et al. 2021]. These SOFIA results help solidify some of the basic science around how solar energy is exchanged between the Earth's surface and space. SOFIA is the only facility in the world capable of making such measurements, which are an important step towards a conclusive understanding of the Earth's upper atmosphere and reliable confirmations of climate model predictions.

Jupiter: Jupiter's atmosphere is primarily molecular hydrogen, which has its fundamental rotational transitions in the mid-IR. H₂ comes in two forms, ortho and para, with an abundance ratio that depends on temperature. FORCAST found a global variation of ortho/para H₂, indicating significant upward mixing of warmer (interior) material in the equatorial regions [Fletcher et al. 2017, de Pater et al. 2021]. The first

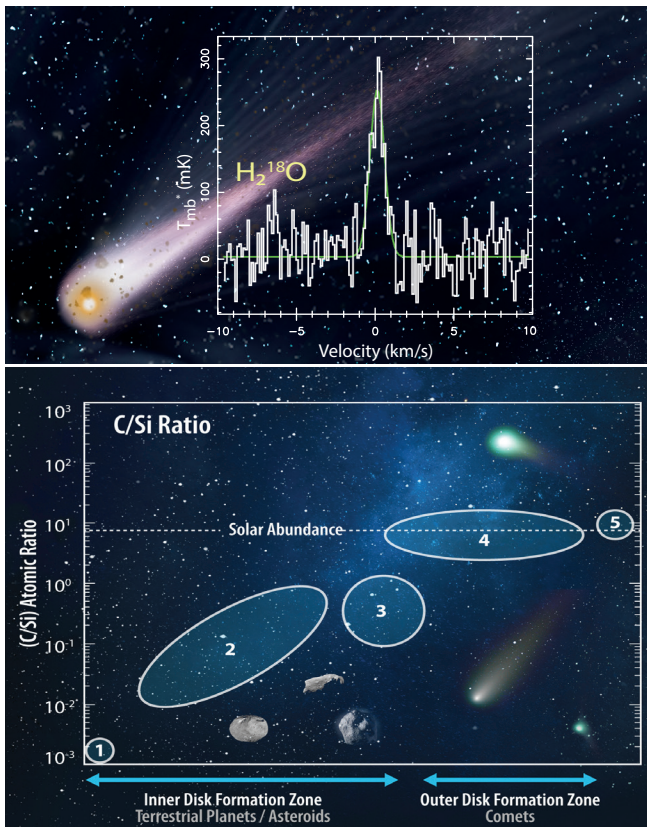


Figure 2-7 (Top) SOFIA observed far-IR transitions of H_2^{18}O (shown) and HDO (not shown) in the coma of comet 46P/Wirtanen and found its D/H ratio to be the same as in the Earth's oceans. (Bottom) Atomic carbon-to-silicon ratio (C/Si) loci for various Solar System objects: (1) the bulk of solid earth, (2) meteorites, (3) interplanetary dust particles, (4) SOFIA-studied comets, and (5) the interstellar medium.

measurement of ortho/para was made by Voyager in 1979, and SOFIA has now measured two epochs, sampling Jovian northern summer and winter to investigate how vertical upwelling changes with different amounts of solar heating. This project complements a JWST Early Release Science project, which will map the planet at wavelengths shorter than $\sim 11 \mu\text{m}$ (whereas the ground-state ortho and para features are at 17 and 28 μm). SOFIA is also studying how the interaction of solar wind with Jupiter's magnetosphere affects its chemistry by comparing the distributions of CH_4 , CH_3 , and C_3H_4 across its disk with Jupiter's ultraviolet and near-IR auroral emission measured by the Juno spacecraft.

Titan: The largest moon of Saturn has the only thick atmosphere in the Solar System. It is primarily composed of CH_4 and N_2 , giving rise to a rich chemistry of organic molecules. EXES is observing these aromatics and heavy hydrocarbons, as well as molecular isotopologs and isomers. The wavelengths needed for these observations are inaccessible from the ground (16-25 μm) and the spectral resolution needed is 100x higher than that achieved by fly-by missions or JWST. Seasonal changes in HCN, C_2H_2 , and C_2H_6 caused by interactions with the Sun and Saturn can be

monitored with repeated observations. SOFIA's potential for Titan atmospheric studies and astrobiology is unique, complementary to a JWST guaranteed time investigation, and addresses the variation of the atmosphere on timescales of Titan's and Saturn's orbits.

2.3 Time-Domain Studies and Multi-Messenger Astrophysics

The 2020s are a unique time when astrophysical observatories cover nearly every electromagnetic waveband as well as neutrinos, cosmic rays, and gravitational waves. Multi-epoch spectroscopy, such as Jupiter's ortho/para ratio in support of JWST (§2.2.2), and unique occultation opportunities such as that of Pluto in coordination with the New Horizons mission [Person et al. 2020], are key to obtaining a time-domain, panchromatic view of astrophysical phenomena. But because much of the luminosity from a wide range of astrophysical objects is emitted in the IR, measuring a fundamental quantity, total energy, also requires an IR observation. SOFIA is the only far-IR observatory, and without it the astronomical community would be blind to this critical part of the spectrum. A complete suite of capabilities is ready to follow up on unique events and discoveries in either hemisphere.

2.3.1 Accretion Bursts in High-Mass Protostars

How Do Protostars Accrete from Envelopes and Disks, and What Does This Imply for Protoplanetary Disk Transport and Structure? (F-Q3b)

Theory has long suggested that the mass growth of protostars occurs stochastically in a series of episodic accretion events from the surrounding disk. In fact, episodic accretion may be one of the most important processes in the later stages of star formation, accounting for about 25% of a star's final mass.

Because most of the accretion energy is emitted in the far-IR, the outburst luminosity and time development can only be measured with SOFIA. For a rare, high-luminosity accretion event in the 20 M_{\odot} protostar S255IR [Caratti o Garatti et al. 2016], FIFI-LS measured both the mass accreted ($\sim 2 M_{\text{Jupiter}}$) and the energy released ($\sim 10^{46}$ erg) during the burst, which was three orders of magnitude higher than any previously observed accretion event from lower-mass stars. SOFIA observations of a second accretion burst show that NGC 6334 I-MM1 became the brightest far-IR source in the protocluster (Figure 2-8) and the brightest accretion flare on record [Hunter et al. 2021]. Although that outburst continues to be bright, a third source, G358.93-0.03, has undergone slow decay to pre-outburst levels [Stecklum et al. 2021].

These results substantiate the predictions of disk fragmentation models and radiation hydrodynamic simulations, while ruling out alternatives like stellar mergers.

The data also confirm that high-mass stars may form like their less massive siblings, namely from collapsing interstellar gas and dust clouds, ultimately gathering the infalling material in an accretion disk.

Quantitative observational research on stochastic accretion is hampered by having only a few examples. Two of these outbursts were preceded by a flare in the circumstellar 6.7 GHz methanol maser emission. Since such masers are radiatively pumped by mid-IR photons, flares signal an increase in IR luminosity. Using the methanol maser monitoring programs already in place, luminous, high-mass accretion events should be much more frequently recognized in the coming years, thereby greatly increasing the sample available for study with SOFIA.

2.3.2 Supernovae (B-DA)

When a supernova explodes in the Milky Way, astronomers should be ready to learn all they can. The explosion of SN 1987A in the LMC was forefront on the astronomical community's mind and in every newspaper and science magazine. While only 25 neutrinos were detected in 1987, more detections can be anticipated with coordinated, rapid follow-ups that will be triggered by the SuperNova Early Warning System (for neutrinos), coming online in 2025. Amateurs or professional astronomers (e.g., LSST) will quickly discover the event, which will ultimately yield sweeping changes throughout astrophysics. SOFIA is soliciting a team to prepare for such a dramatic event, by encouraging community proposals of observations to occur in the event of a nearby supernova. The Supernova Team, to be selected in Cycle 10, will then develop a coordinated observing plan and tune it when an event occurs. For SN 1987A itself, SOFIA has monitored its dust evolution, discovering that dust re-formed in its post-shock regions over the last decade. The dust yield of supernovae is a critical ingredient for understanding early galaxy evolution, with dust forming, then being destroyed in the reverse shock, then evidently forming again, enabling supernovae to create dust in early galaxies [Matsuura et al. 2019].

2.3.3 Stellar Mergers (G-Q2)

About half of all stars are binaries, and the end state of some of those systems is for the two stars to merge. LIGO recently detected the decay of neutron-star orbits due to gravitational wave generation, and non-degenerate stars (V1309 Sco, V838 Mon, V4332 Sgr) also merge. The wide range of outcomes being observed with the advent of time-domain astronomy is extending our former knowledge of supernovae and novae to a panoply of explosions and remnants. SOFIA observations will characterize bolometric luminosity (for the cooler events) and interaction with circumstellar and interstellar matter. A similar class of binary interaction in symbiotic stars occurs when a degenerate star is

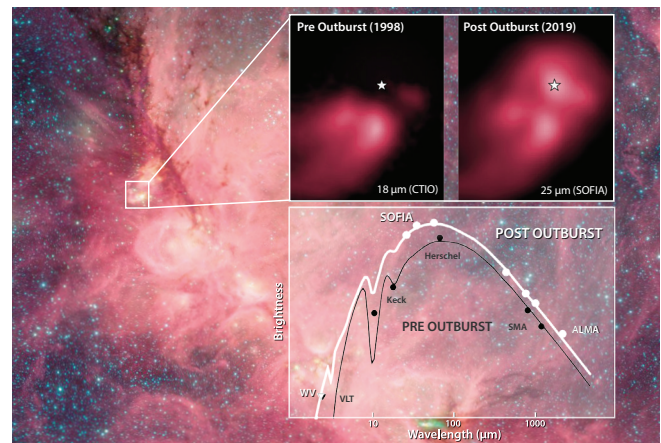


Figure 2-8 Accretion outburst in the Cat's Paw Nebula. Insets show the region of the high-mass protostar NGC6334 I-MM1 (location shown with the star symbol) with post- and pre-outburst luminosity, imaged by SOFIA and CTIO, respectively, as well as the pre-outburst (blue) and post-outburst SEDs. Background image from Spitzer.

on an eccentric orbit and plows through the outflow or outer atmosphere of a giant companion star. Multi-epoch observations by SOFIA of the symbiotic binary star system R Aqr showed that stellar pulsations and the orbital period of the binary cause repeatable variations in the circumstellar dust density [Omelian et al. 2020]. The silicate feature evolution in the stellar merger V838 Mon shows fresh dust is forming [Woodward et al. 2021].

2.3.4 Great Dimming of Betelgeuse (G-Q3)

In 2020, a nearby red supergiant star, Betelgeuse, underwent a "great dimming" event of unknown origin. SOFIA observations showed velocities at 3–20 stellar radii were unchanged, while conditions in the dust-forming and outflow-originating region were significantly different from the few prior observations made with the Kuiper Airborne Observatory [Harper et al. 2020, 2021]. High spectral resolution observations that address different altitudes in the stellar atmosphere and outflow are uniquely possible with EXES and GREAT in the mid- and far-IR.

2.3.5 Planetary Disruptions (E-Q1)

Dusty "debris disks" are thought to evolve via collisions and evaporation of solid bodies, ranging from small planetesimals to larger planet-sized objects. Dust in these debris disks is typically low-temperature (≤ 100 K) and orbits far from the host star, similar to the Kuiper Belt in our own Solar System. Measurements by SOFIA of the variability of dust in circumstellar debris disks led to the discovery of a population of transient grains around HD 113766 [Su et al. 2020] and BD +20 307 [Thompson et al. 2019]. These grains are the result of recent violent impacts between large asteroidal or planetary bodies. Studying warm debris disks gives astronomers a rare opportunity to examine compositional changes of circumstellar material that vary on extremely short timescales and to better understand

catastrophic collisions that occur late in the formation history of a planetary system. As more anomalous debris disks are discovered, time variation may potentially be detected with the Vera Rubin Observatory. SOFIA will remain uniquely poised to measure far-IR brightness to complement mid-IR observations from JWST.

3. SCIENCE OPERATIONS

SOFIA maintains a state-of-the-art instrument suite covering more than three magnitudes in wavelength range which complements other contemporary facilities and allows SOFIA to address more than half of the Astro2020 fundamental science questions (§2). SOFIA selects and plans world-class science observations; provides user support and funding; delivers reliable, science-ready data; and is expanding its user base to engage our entire, diverse community.

3.1 Science Instrument Suite

SOFIA's instrument suite (Figure 3-1) provides continuum, spectroscopic, and polarization imaging in the full mid-IR and far-IR wavelength range inaccessible from the ground. SOFIA's unique capabilities address one half of the Astro2020 science priorities and all three of the SMD astrophysics questions (Table 1-1 and §2). The spectral resolving power of SOFIA provides measurements not possible with any other observatory. Unlike space-based IR facilities, its instrument detectors don't saturate even on the bright targets, many of which serve as local templates for understanding the distant Universe (Figure 3-1). Thus, SOFIA has science synergies with several concurrent observatories, especially JWST and ALMA.

3.1.1 Instrument Management

SOFIA science instruments are developed by Principal Investigator (PI) teams selected through a competitive proposal process. The team either delivers their instrument to the observatory as a Facility Science Instrument (FSI; includes FORCAST and HAWC+) or supports it as a Principal Investigator Science Instrument (PSI; includes FIFI-LS, EXES, and GREAT). FIFI-LS and EXES transitioned to FSI in 2015 and 2021, respectively, and funding for GREAT is secured through 2023 (Cycle 11).

The observatory operates with a single instrument at its Nasmyth focus and all instruments remain in high demand (Figure 3-2). FORCAST and GREAT are the most mature of the instrument suite and their observations have produced the most publications. The newest addition, HAWC+, is already in high demand and has produced high-profile results.

New instruments and upgrades are solicited to enhance the present instrument suite and enable high-impact science (§5.6). With finite resources and observing time, the observatory balances the

commissioning of newer instruments with the retirement of older instruments. Such decisions are thoroughly vetted within SOFIA and NASA, aided by input from the community through the SOFIA User Group and a Science Instrument Analysis Group.

3.1.2 Synergies with Other Observatories

SOFIA is a critical component of NASA's astrophysics portfolio, complementary to other facilities (Figure 3-1). SOFIA enables high-resolution spectral observations in the waveband where normal galaxies and star-forming regions emit the most energy. This unique wavelength

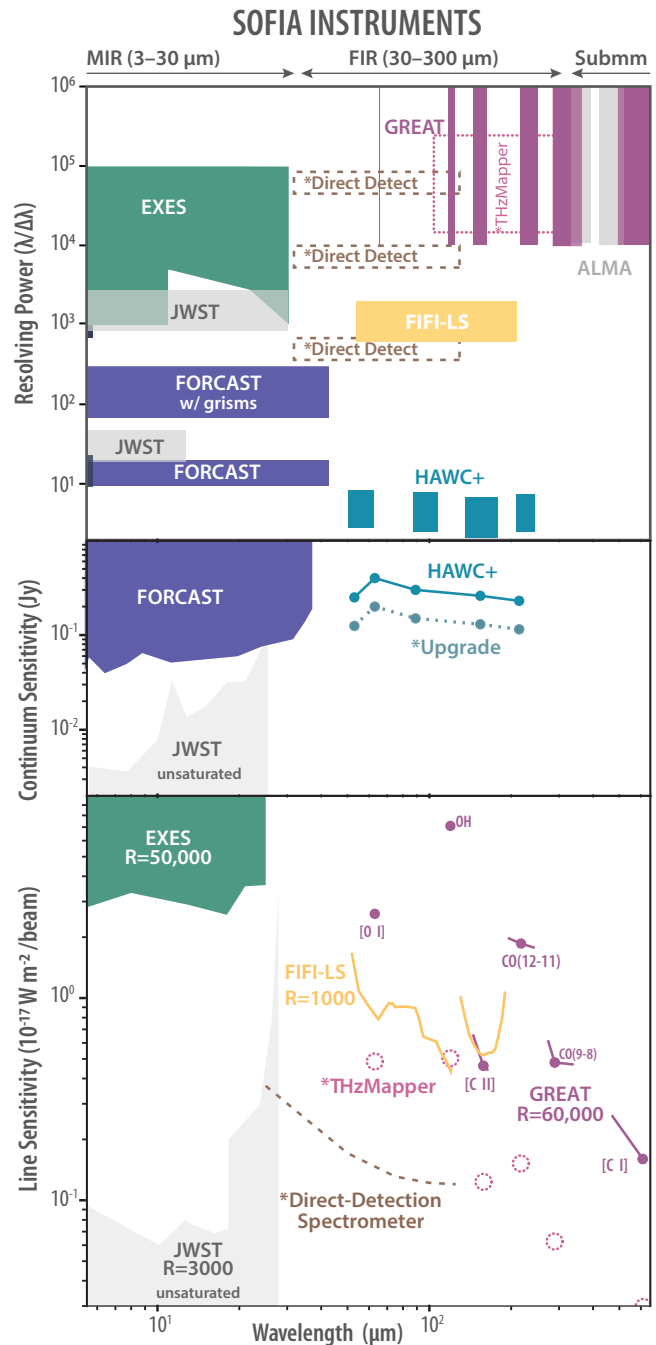


Figure 3-1 The SOFIA Science Instrument suite. Current instruments are shown in colors, and instrument development concepts are dashed or dotted. They are complementary to JWST and ALMA, which are depicted in grey.

range is longer than is accessible to JWST and shorter than is accessible to ALMA. The molecular transitions visible only to SOFIA offer fundamental insight into a variety of astrophysical phenomena, for instance enabling distinct views of planets and planet-forming disks around young stars that are complemented by observations from other facilities. Future instrument concepts (§5.6) will extend SOFIA's far-IR line mapping of star-forming regions and galaxies (Terahertz Mapper) and of the cold gas of planet-forming disks (Direct Detection Spectrometer). SOFIA has an efficient, wide-field mapping capability that provides context for JWST and ALMA observations.

SOFIA is the ideal platform for studying the bright, nearby Universe where JWST is saturated. The nearby Universe is key to illuminating and setting the schemas for the underlying physics in more distant objects. In the Solar System, SOFIA can observe targets at elongations not possible with JWST; e.g., Venus, the Moon, and Earth.

Balloon missions such as GUSTO and BLASTPol provide direct scientific synergy to SOFIA by performing even wider-area surveys or pathfinder science of select regions. The capabilities of these facilities complement SOFIA, whose large telescope, evolving instrument capabilities, and frequent flights offer open access to a much larger observer base. Balloon projects can advance instrumentation to higher technology readiness levels that can then be used by SOFIA. SOFIA instruments can in turn serve as prototypes for future large space missions; for example, HAWC+ served as a prototype for the Far-Infrared Imager and Polarimeter instrument concept in the Origins Space Telescope study.

3.2 Science Observations

3.2.1 Selection

The distribution of SOFIA observing time is shown in Figure 3-2. Observing time is split 80/20 between the US and Germany, with US time open to the international community. SOFIA selects Guest Observer (GO) proposals based on peer-reviewed scientific merit, determined by a Time Allocation Committee (TAC). Although analyses of earlier cycles found no bias, SOFIA implemented a dual-anonymous selection process in Cycle 9 to ensure that proposals are not biased by gender, race, seniority, or notoriety. Accepted projects are grouped into tiers based on their scientific merit: Priority 1 ("Will Do", 25% of observing time), Priority 2 ("Should Do", 50%), and Priority 3 ("Do if Time" >25%). Priority 3 projects are over-selected so there is a deep pool to generate full and efficient

SOFIA OFFERS DIVERSE CAPABILITIES LIKE HIGH-RESOLUTION SPECTROSCOPY AND FAR-IR POLARIMETRY TO ADDRESS THE FUNDAMENTAL QUESTIONS POSED BY ASTRO2020.

flight plans. The historical program completion rate of Priority 1 and 2 programs is shown in Figure 3-3. To increase completion rates toward our 80% goal, SOFIA has adjusted its policies, including improved technical review of proposals, two-year execution windows for Priority 1 and 2, and addition of contingency flights to cover weather and technical outages.

Legacy programs are designed to create rich archival datasets. They span two cycles, and data are released immediately to the community. A Legacy program goes through an initial "pilot" phase to demonstrate its feasibility. It is then reviewed and can be promoted to complete its entire program.

SOFIA added an innovative Thesis Enabling Program category, aimed at enhancing the financial support for and execution of doctoral theses based substantially on SOFIA observations. Acceptance of a Thesis Enabling program leads to guaranteed funding for a graduate student, so grants do not have to be combined from multiple funding sources.

Director's Discretionary Time (DDT) is intended for time-critical phenomena, small programs that complete a thesis or paper, or high-risk/high-reward observations. DDT proposals can be submitted at any time. The scientific and technical merit of DDT proposals is determined by external scientific review and internal assessment of feasibility. Successful examples include the detection of water on the sunlit surface of the Moon and multi-instrument studies of the unexpected dimming of Betelgeuse in 2019/2020.

New initiatives started in Cycle 9 will stimulate scientific productivity and expand the SOFIA user base. To encourage quicker publications, the default exclusive-use period for SOFIA GO observations was reduced from 12 to 6 months. Cycle 9 features a joint SOFIA/Green Bank Telescope Call and solicited observations to support JWST Early Release Science and Guaranteed Time programs. Cycle 9 also features

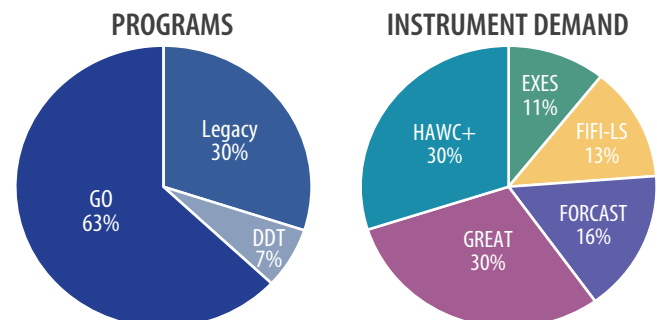


Figure 3-2 Division of SOFIA observing time and SOFIA Science Instrument demand in Cycle 9.

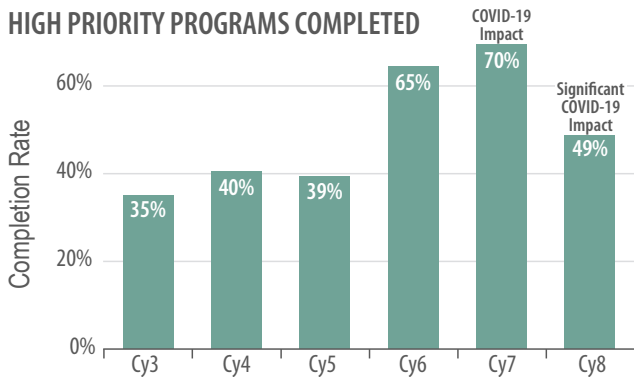


Figure 3-3 Completion rate of priority 1 and 2 programs. Cy8 programs impacted by COVID are being observed in Cy9

multiple deployments to the Southern Hemisphere, increasing access to astronomical targets in the southern skies. Workshops and user support have been increased to help users overcome any data-related barriers to publication. A SOFIA Archival Research Program (SARP) commenced in Cycle 9 with grant funding for up to two years and achieved a funding oversubscription rate of 3.9. SARP attracted new PIs/Co-Is to SOFIA, with 46% of the proposals awarded to early-career scientists. SOFIA will continue this program with \$1M-\$2M in annual funding.

3.2.2 Planning

SOFIA plans for ~1300 hours on the sky in Cycle 9 and will reach ~1400 hours in Cycle 10. These observations must be scheduled efficiently within a complex system of constraints. The telescope can observe targets with an elevation between 20 and 60 degrees, while the azimuthal pointing is controlled primarily by aircraft heading. To take off and land at the same airfield, efficient flight plans must balance east-west and north-south bound flight legs. Other unique constraints such as weather, winds, and variable no-fly zones add complexities well beyond those encountered by ground- or space-based observatories.

SOFIA scheduling complexity has been mastered with the help of automated software tools. The Cycle Scheduler generates a year-long calendar of instrument flight series that optimizes the completion of high-priority projects across the entire cycle. The Short Term Scheduler generates millions of simulated flight plans to arrive at an optimal flight schedule. In operations, planning for each flight series (which has a single science instrument) begins ten weeks before the instrument is scheduled to fly. At 36 and 12 hours prior to takeoff, the flight plan is updated with any new weather or air traffic control information and then filed with the FAA or equivalent. This process was streamlined to take minutes to do what used to take up to two hours before Cycle 8. Software automatically generates the data package, containing observations and flight information, which is loaded onto the plane prior to takeoff.

3.3 User Support

SOFIA provides user support to lower barriers for non-experts to utilize the observatory and its data. User support begins with up-to-date web-based documentation for the observatory and a Help Desk. Each accepted observing program is assigned a staff scientist to prepare detailed observation plans, folding in any unique requirements. The instrument scientists create detailed observing scripts for each flight leg, execute the science and calibration observations on board the aircraft, reduce the data into calibrated products, and communicate results to the GOs. The final step in observer support is to guide observers toward publication. A “My Proposals” tool was implemented to allow GOs to see all their present and past projects, observing progress, and data availability.

Observers at US institutions are eligible for grants to support data analysis and publication of results. Priority 1 and 2 observations typically receive \$10K per hour of awarded observing time. Priority 3 observations receive \$10K increments per hour observed. Legacy programs propose a detailed budget with a schedule and management plan for delivery of their high-level data products. Under the Thesis Enabling Program, the PI (normally the thesis advisor) can request up to two years of graduate student funding at the standard rate of the host university. Starting in Cycle 10, SOFIA will issue a minimum award of \$75K per program, regardless of size, to ensure adequate support.

3.4 Data Processing, Archive, and Tools

SOFIA is committed to providing the astronomical community with fully calibrated data in standard formats. These data products, which have been corrected for instrumental and atmospheric signatures, allow observers to begin their analysis quickly and enable archival research by both experts and non-experts.

SOFIA data processing is mature, and the mission continues to improve data quality and data reduction efficiency, for example by implementing algorithms for the new FIFI-LS On-the-Fly mapping mode, new spatial and spectral regridding methods, and the new HAWC+ scanning polarimetry mode. The SOFIA Users Group has advocated for a new initiative to make the pipeline tools and user manuals available to the public to allow the community to review details of how their data were processed. In the past year, all FSI pipelines were released as open source code. EXES, which just recently became an FSI, will have its pipeline released by late 2022.

The SOFIA data products are hosted at the Infrared Science Archive (IRSA), allowing astronomers to search for multi-wavelength data from multiple NASA missions [Luisi et al. 2021; Su et al. 2020]. The SOFIA archive at IRSA has been enhanced to allow keyword

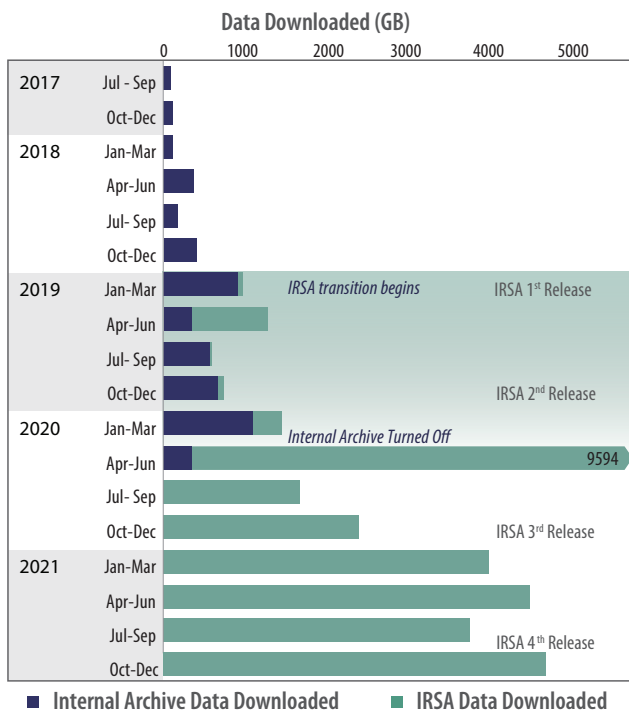


Figure 3-4 Timeline and trends of SOFIA archival usage. Transition to NASA/IPAC Infrared Science Archive (IRSA) from SOFIA internal archive and aggressive IRSA updates have contributed to an increase in the archival usage.

and abstract searches that link to data products, and to include graphical previews of high-level data products. Since the full transition to the IRSA archive, SOFIA has reduced the time-to-delivery of data to IRSA and seen a significant increase in archive traffic (Figure 3-4).

3.5 Science Community Engagement

The SOFIA user community (Figure 5-3) comprises over 2000 investigators and authors, and is growing yearly (12% growth in 2021). Community engagement activities have increased the wider SOFIA community with new-to-SOFIA astronomers by 30% (over 600 people) last year. A key element to this success is holding virtual scientific workshops in areas SOFIA wishes to grow. As of January 2021, three successful workshops were held on Solar System bodies, magnetic fields in filaments, and evolved stars. Invited speakers discussed multi-wavelength observations, theory, and future plans. The attendance at each workshop exceeded 100 participants. The mission plans to hold three to four such science-focused workshops annually.

Redoubling the communication of scientific results through astronomy conferences and colloquia is strengthening the SOFIA community. The efforts include special sessions, displays, and plenary speakers at AAS and AGU meetings. The mission has held many webinars to help the community understand SOFIA's capabilities and processes. SOFIA is organizing a "Galactic Ecosystems" conference for February 2022. User support staff also prepare blog posts and

spotlights for the SOFIA websites, describing the latest discoveries from the observatory. SOFIA eNewsletters are distributed regularly by email to inform and engage the community, and Newsletters are distributed at AAS meetings to present SOFIA's latest results.

Starting in 2022, SOFIA is introducing a school geared towards early-career astronomers and planetary scientists (graduate students and postdocs). This school will be hosted at NASA Ames and provide training in mid-IR and far-IR astronomy, observing, and data analysis. New internships and co-op programs are targeting minority-serving institutions to offer engaging learning experiences and address the NASA workforce, recruitment, and diversity initiatives.

4. PROGRESS SINCE LAST REVIEW

4.1 Responsiveness to the 2019 Flagship Mission Review

The SOFIA mission went through a rigorous peer review in 2019 called the Flagship Mission Review (FMR), in lieu of the 2019 Senior Review. The aircraft was reviewed separately by a team of aircraft and aviation experts in the SOFIA Operations and Maintenance Efficiency Review (SOMER), referred to as the "aircraft review" in this document. The mission made many transformative changes in a short amount of time in response to the FMR to set SOFIA on a path to higher productivity and impact. The mission's plans to address this review are discussed in detail in the FMR Response Report², and its rapid and positive responsiveness to the review can be found throughout this proposal. Table 4-1 summarizes the actions taken to address the ten specific recommendations of the FMR report. Table 4-1 also indicates the sections throughout this proposal where there is deeper discussion of the related positive initiatives and changes. As they are not discussed in similar detail elsewhere in this proposal, additional discussion of some of these recommendations is warranted here.

Nurture a Science-Driven Culture and Embrace Change

SOFIA leadership made significant structural changes that nurture a science-driven culture and allow the organization to embrace change. Resources have been invested into hiring three new instrument scientists, two new science outreach staff, and six postdoctoral researchers. Research productivity has also been made a performance evaluation goal for each SMO scientist. These changes have resulted in a *two-fold increase* in science research time charging and a *two-fold increase* in staff publications. The enhanced science outreach team has increased talks and virtual conferences for our staff and SOFIA community. The postdocs are working on SOFIA projects with staff and

² <https://www.sofia.usra.edu/FMRresponse>

improve the scientific environment with their fresh ideas and energy.

SOFIA has embraced change in operations, instrumentation, data delivery, metrics, science outreach, and time allocation, as described in new initiatives throughout §3. Science and Mission Operations have become more efficient through automation and cross-training of staff, and savings from this area were invested in science. The instrument swap time has been reduced from three days to two days for all facility-class science instruments. SOFIA has an improved data interface in the IRSA and a more efficient and faster delivery of data to IRSA. After discussions with STScI and Chandra, SMO established a consistent and automated approach to its publication metrics. The SMO has implemented joint science endeavors with a number of observatories (e.g., ALMA, Green Bank, IRTF). SOFIA staff are meeting with other observatories to exchange best practices and lessons learned on a range of processes, with two recent such meetings concerning data pipelines and grant management.

“The APAC applauds recent efforts to improve the scientific productivity of SOFIA... SOFIA also has made pivot towards a more effective utilization of archive products and broader investigator flight opportunities to yield better cost per dollar on investment as the Project commences its extended mission.”

NASA HQ Astrophysics Advisory Committee, March 2021

Split Aircraft And Science Operations

The FMR report included the programmatic recommendation from the aircraft review to separate the SOFIA program into two separate projects, one focused on operations and one focused on science. Although this recommendation was not fully accepted by the project, SOFIA did execute organizational changes which address the core intent of this FMR recommendation by separating the aircraft operations and science operations functions within a new single project (Figure 7-1). Consideration of separating the

aircraft operations from the observatory operations, with special consideration of the Airborne Science Program operating the SOFIA aircraft, was pursued, but was found to be not feasible, inefficient, and having the potential of hurting the scientific productivity of the mission. In addition, because SOFIA is a post-prime mission, the Project must take increased mission assurance risk. Much of the increased risk takes the form of lower funding of aircraft and observatory staffing, which results in a reduced ability for the aircraft

Table 4-1 Response to the Flagship Mission Review Recommendations

Rec. No.	Proposal Sections	Specific FMR Recommendations	In Progress	Completed	Implementation Details
1	5.2	Nurture a science-driven culture within the mission		Y	Significantly increased science and outreach staff, transformed operations through automation and cross-training, shortened instrument swap times, implemented aggressive science community outreach
2	5.3	Embrace change in operational approaches			
3	3.2 5.1	Emphasize completion of high-priority science programs		Y	Addition of contingency flights, more thorough technical review of proposals, automatic rollover of incomplete programs to next cycle
4	5.1	Emphasize the collection of high-quality data	Y		Scheduling of annual aircraft maintenance when observing conditions are poorest, using water vapor instead of altitude, using water vapor forecasts to fine-tune which flights to fly, flying more Southern Hemisphere flights in humid northern summer
5	5.3 6.7	Maximize observing time at stratospheric altitudes			
6	5.1 6.7	Fly more Southern Hemisphere flights	Y		Doubling the annual number of Southern Hemisphere flights
7	3.4	Transfer data products into the archive quickly		Y	Flight-by-flight processing rather than series-by-series; more staff cross-trained to perform data processing
8	7.3	Split aircraft operations from telescope/science operations		Partial	The core intent was addressed. SOFIA Project decided against fully implementing this recommendation after exhaustive study.
9	5.6	Invoke HIRMES cost and schedule control	N/A	N/A	HIRMES was terminated in 2021 by NASA SMD, citing significant technical, cost, and schedule risks.
10	3.1 5.6	Focus on current science operations rather than future science instrument development	Y		EXES transitioned to a facility instrument to be more productive, planning begun for a HAWC+ upgrade, increasing southern access to more instruments

Table 4-2

Response to the Astro2020 Decadal Comments on SOFIA

The 2020 Decadal Committee strongly expressed the importance and effectiveness of the NASA Senior Review process for setting funding priorities, and for establishing criteria and a decision process for terminating missions [Astro2020, section 5.2]. Since SOFIA was not included in the 2019 Senior Review, Astro2020 recommendations for SOFIA were based on the findings of NASA's FMR and aircraft reviews from June 2019 [Astro2020, section 5.2.1].

The data used by the Decadal Committee was more than two years old. Over that time period, the SOFIA mission transformed under the new leadership (§7) and by following guidance from these two NASA reviews (§4.1). This proposal, prepared for the 2022 Senior Review, clearly demonstrates that transformation and the promise of greater scientific productivity and impact over the next three years. Table 4-2 directly addresses the concerns raised in the 2020 Decadal Survey report.

Astro2020 Comments on SOFIA [†]	SOFIA Mission Response
"...SOFIA performs mostly Northern Hemisphere...and spends a smaller fraction of the year in the Southern Hemisphere..."	In 2021, SOFIA increased observing time in the Southern Hemisphere by a factor of 2. §5.1, 6.7
"... The NASA portion of SOFIA's operating budget is \$86 million a year, of which \$4 million goes to Guest Observers for data reduction and analysis..."	SOFIA provides \$10,000 per observing hour, which is comparable to other NASA observatories. Since total observing time on an airborne platform like SOFIA is lower than space observatories, the total GO funding is proportionally lower. SOFIA is now additionally funding GO archival research and has established a minimum grant funding threshold of \$75K. SOFIA additionally invests \$5M (annually) in the community by funding development of new instruments and operations upgrades to improve efficiency. §3.3, 5.6
"... For this investment, the science productivity to date is very low... The science impact is also low..."	SOFIA's growth in publication and impact (citations) has recently passed an inflection point and is on the rise. SOFIA doubled its publication over the last three years and citations are growing exponentially. Growth will continue due to a ~50% increase in observing time. §5.7
"... ESA's Herschel mission, was, like SOFIA, a flagship scale mid-to-far-infrared facility, which saw nearly 900 peer-reviewed papers in the 6 years following launch..."	Herschel completed 22,000 hours of data collection over 3.5 years of its mission lifetime (2009-2013). SOFIA being an airborne platform has collected ~4000 hours of scientific data since 2010, about 18% of the total Herschel observing hours. This translates roughly to 160 Herschel publications (18% of 900). SOFIA has about 300 peer-reviewed science papers, 50% more than Herschel over the same amount of observing time. Over SOFIA's operational lifetime of 20 years, it is expected to have the same or better scientific productivity compared to Herschel. §5.7
"... SOFIA directly addresses three of the thirty priority science Questions... therefore minimal overlap of the Astro2020 Panels' science priorities with SOFIA capabilities..."	SOFIA contributes to fifteen of the thirty Astro2020 science priorities. §1; Table 1-1
"... There is significant down time in each year for necessary airplane maintenance..."	Starting 2021, observatory down time for FAA-mandated maintenance is consolidated to 5-6 weeks annually, increasing time for science observations. §5.1
"... With a typical ~1000 flight hours per year, and a relatively modest 60 percent of programs being completed, and 60 percent of these turning into peer-reviewed publications, only a few percent of total yearly calendar hours are turned into peer-reviewed science, an order of magnitude less than other astronomical observatories..."	Flight hours have increased to 1500 starting 2021 and will increase to 1700 starting 2022. §5.1 Program completion rate is increasing (Figure 3-3). It reached 70% in one of the recent cycles even with the COVID-19 impacts. Several initiatives have been implemented and more are planned to promote faster publications. §5.7
"... The survey committee found no evidence that SOFIA could, in fact, transition to a significantly more productive future. There have been only modest improvements in productivity over the past 2 years..."	SOFIA has transformed over the last two years (since early 2020) by implementing all the recommendation of the FMR and taken bold initiatives to increase observing time in both hemispheres. Sections 3 and 5 of this proposal strongly demonstrate this progress and promise of continued success. §3, 5, 7
"... the SOFIA team has responded to NASA that... major recommendations from... reviews are not feasible to implement, suggesting any future improvements would still be modest..."	SOFIA mission has addressed all the recommendations of the flagship mission review. §4.1
"... the survey committee found no path by which SOFIA can significantly increase its scientific output or relevance to a degree that is commensurate with its cost..."	SOFIA has transformed over the last two years by implementing all the recommendations of the FMR and taken bold initiatives to increase observing time in both hemispheres. Sections 3 and 5 of this proposal strongly demonstrate this progress and promise of continued success. §3, 5, 7

[†]From page 5-11 and 5-12 of the Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2021) [Astro2020]

and integrated observatory to be ready for flight as planned. This increased mission assurance risk would be very difficult to manage across two separate organizations, so the management of SOFIA mission assurance risk, performance, and budget will remain within a single project structure.

Invoke HIRMES Cost and Schedule Control

The next-generation instrument HIRMES was terminated in 2021 by NASA SMD, citing significant technical, cost, and schedule risks. In response, and in coordination with SMD and the astronomical community, SOFIA has laid out its vision for future instrumentation in the Instrument Roadmap (§5.6).

Focus on Science Productivity of Current Science Instruments

The Project has made significant progress on increasing and maximizing the scientific potential and productivity of current SOFIA instruments. As discussed in §5.3.2, several SOFIA instruments, including FIFI-LS, HAWC+, and FORCAST, have recently completed (or are in the processing of implementing) new and more efficient observing modes. §5.1 describes how SOFIA will expand the number of instruments offered to the community for Southern Hemisphere observations. §5.6 describes the substantial investment being made to upgrade HAWC+, SOFIA’s workhorse instrument. This upgrade will increase its mapping speed by up to a factor of at least four, enabling ambitious Legacy programs. Recently, EXES transitioned to a facility instrument, increasing observing flexibility.

Additionally, the Project funded data pipeline development and archiving of EXES’s sister instrument, TEXES, on NASA’s IRTF, to make these complementary data sets more readily accessible and usable for SOFIA users. TEXES data will be also be hosted on IRSA and publicly available. The Project also funded essential upgrades to the GREAT local oscillators to meet the community’s demand.

4.2 Response to 2020 Astrophysics Decadal Survey

Table 4-2 directly addresses the concerns raised in the 2020 Decadal Survey report.

5. PATH FORWARD: HIGHER PRODUCTIVITY AND GREATER IMPACT

Building on the successful implementation of the FMR recommendations outlined in §4, the mission is continuing on a bold and transformative path. Table 5-1 outlines the Prioritized Mission Objectives (PMOs), which will drive SOFIA to the next level of scientific productivity, impact, and efficiency.

5.1 Increasing Observing Opportunities

Increasing both Northern Hemisphere and Southern Hemisphere observing opportunities (within a lower operating budget than the prime mission) is one of the most direct paths to increasing SOFIA’s scientific return, enabling ambitious observing programs, and growing the SOFIA user community. The Project executed two major operational changes starting in Cycle 9 (July 2021): (1) the adoption of once-a-year annual observatory maintenance compared to three maintenance periods per year, freeing up more time in the year to schedule flights; and (2) implementing a weekly contingency flight, to make up for lost flights due to weather or technical issues. Figure 5-1 shows the planned increase in science flights offered to the community (green line) and the achieved science flights (black line). The projection (dashed) assumes an 80% success rate based on historical trends. The shaded region shows the potential of contingency flights in boosting the number of achieved flights. The addition of contingency flights is expected to boost the completion rate (Figure 3-3) of the awarded observing programs (current best completion rate is 70%). The success of these two operational changes will be realized over the next few years and is expected to increase the actual observing opportunities by 50%.

As part of the continuing program to maximize SOFIA productivity, the observatory has investigated ways to acquire data under best observing conditions. A detailed study in 2020 concluded that SOFIA is presently doing an excellent job of observing in low water vapor conditions. Specifically, the precipitable water vapor (PWV) data for all SOFIA flights since 2014 show “very good” observing conditions (< 15 μm) for more than 90% of the observed research hours and “excellent” observing

Table 5-1: 2022 PRIORITIZED MISSION OBJECTIVES

§5.1	Implement new observing opportunities for Northern and Southern Hemispheres. (PMO 1)
§5.2	Grow SOFIA community. (PMO 2)
§5.3	Increase science return by 10% with innovative improvements to science operations. (PMO 3)
§5.4	Prioritize Legacy programs to enhance SOFIA archival value. (PMO 4)
§5.5	Develop time domain for far-IR astronomy to support multi-messenger science. (PMO 5)
§5.6	Increase SOFIA science discovery space with upgraded or new instrumentation. (PMO 6)

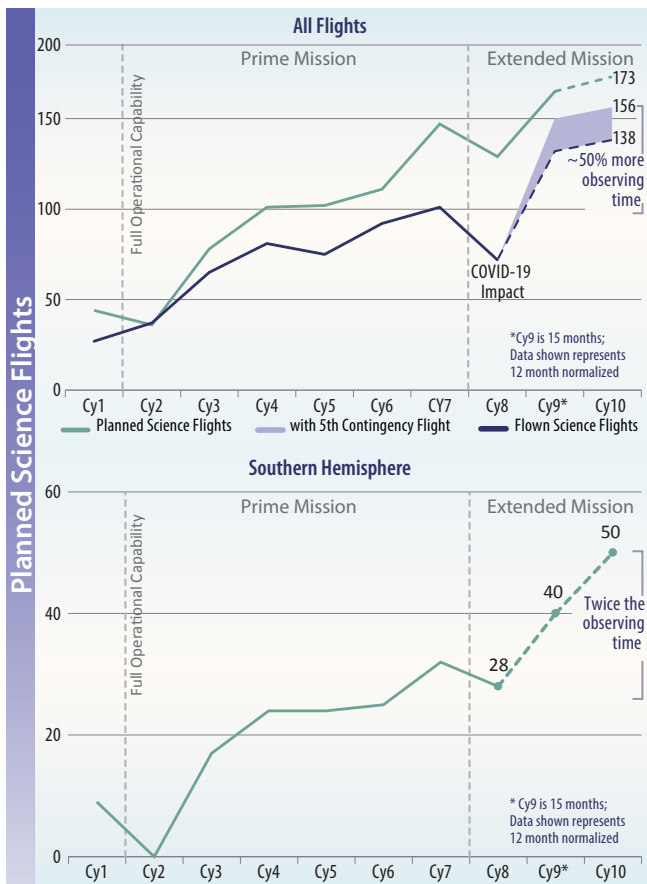


Figure 5-1 Historical trend for planned (green) and achieved (black) science flights. Projections for Cycles 9 & 10 are shown by dashed lines. The research hours offered to the community are directly proportional to the science flights planned.

conditions ($< 10 \mu\text{m}$) for 76% of the observed research hours. Another key finding from this study was how the PMV varies with season at stratospheric altitudes. Figure 5-2 presents the ideal SOFIA observing schedule that would maximize “excellent” observing condition opportunities. In response, the Project scheduled the annual maintenance period in late summer/early fall when observing conditions for flights originating from Palmdale are poorest. The specific placements of the two short deployments in the Fall and Spring months enable observations of southern targets not previously observable with SOFIA.

Fly 50 Flights in the Southern Hemisphere

Southern Hemisphere observing time on SOFIA is scientifically valuable, allowing access to the galactic center, Magellanic Clouds and other targets

inaccessible from the North and with a ~50% higher over-subscription. To meet the community’s demand, SOFIA will double the number of annual southern flights compared to the prime mission (Figure 5-1) using an efficient concept of operations described in (§6.7). Instead of conducting 50 flights in a single deployment, which is very stressful on the staff and crew, the Project will add two short deployments (8–10 flights) to the annual long deployment (~30–32 flights). The short deployments will be conducted in the Fall and Spring months. With three annual deployments, it will be easier to offer all instruments for southern observing.

SOFIA evaluated southern basing sites having greater flexibility to conduct short deployments when science requires it and as geopolitical situations change. Six suitable alternative bases were identified, some within nonstop range of Palmdale. Among the top candidates were Santiago, Buenos Aires, and French Polynesia. SOFIA deployed to French Polynesia in July 2021 for the first time, and will conduct a short deployment out of Santiago in March of 2022.

5.2 Growing the SOFIA Community

SOFIA currently has ~400 unique PIs and ~2000 unique users: PIs, Co-Is, authors, and co-authors (Figure 5-3). With the goal of growing the user base to 3000 by FY25, initiatives like science workshops are attracting new astronomers to the SOFIA community and encouraging them to engage with SOFIA data (§3.5). New initiatives outlined below are expected to attract even more new astronomers to SOFIA. Most importantly, this PMO supports the Astro2020 recommendation for a future far-IR probe and Great Observatory missions by training and developing the astronomers who will define, develop, and use them.

5.2.1 SOFIA Postdocs

Much of the scientific vigor of an institution comes from a strong group of postdocs. As junior scholars, postdocs tend to know and appreciate the very latest discoveries, theoretical ideas, and trends in the field. They are also extraordinarily productive in publishing papers. Until recently, SOFIA’s few postdocs were grant-funded, but a new group of mission-sponsored postdocs was recruited and hired in FY20 and FY21. These postdocs were assigned strategically to the SOFIA instrument teams to help to drive a science culture within the center. This investment in the future

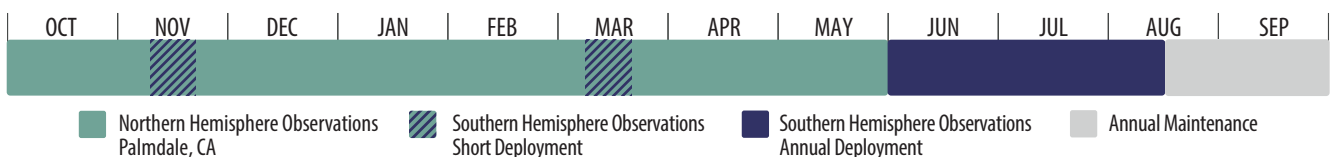


Figure 5-2 Ideal observing schedule that maximizes high-quality observing conditions over an annual cycle. SOFIA has transitioned to once a year maintenance creating room for two additional short Southern Hemisphere deployments (hashed purple) in addition to the annual long deployment (purple).

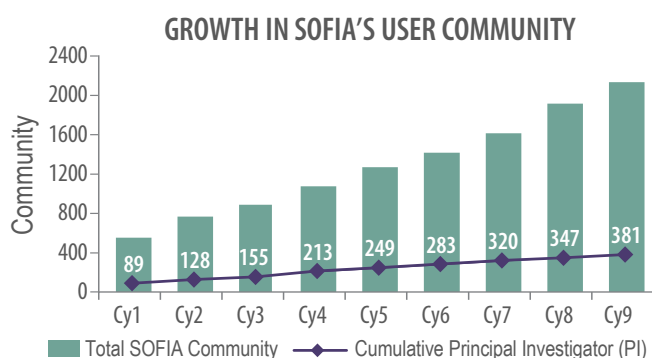


Figure 5-3 Growth of SOFIA community over the last 9 observing cycles. The bars show the total community size that includes PIs, Co-Is, authors, co-authors, and archival users. The solid line shows specifically the growth in unique PIs. Cycle 9 started July 2021.

is already paying off as these new postdocs enhance SOFIA's scientific productivity and impact (§5.7).

5.2.2 Expanded Observing Opportunities

In addition to the Legacy, Thesis Enabling, and DDT initiatives described in (§3.2.1), SOFIA will begin advertising a biannual schedule where all instruments get an observing opportunity in the Southern Hemisphere. This initiative provides the best viewing for the Galactic plane, the richest part of the sky for IR targets. EXES will be part of the southern deployment for the first time in Cycle 10. Setting this long-term schedule means that SOFIA is exposing the full suite of instruments to the best conditions for Galactic-plane astronomy. Now potential users can take advantage of these opportunities and plan far in advance to obtain southern targets with the instruments offered.

5.3 Increasing Science Per Flight

SOFIA continues to implement new initiatives to improve efficiency, produce higher-quality scientific data products, grow our user base, and increase cost savings. The mission is presently implementing a series of improvements and planning for future enhancements to conduct more science per research hour.

5.3.1 Efficient Scheduling using Weather Prediction

Large seasonal variation in the water vapor overburden can impact the sensitivity of observations. Implementing a new “smarter scheduling” approach where the duration of observations will be adjusted based on predicted water vapor overburdens will allow SOFIA to schedule at least 15% more science per nominal research hour. The differences are most notable for targets that are observable from either Palmdale or New Zealand in the northern summer months. In May-August, a typical HAWC+ target can achieve the same S/N in 25-50% less time if observed on a flight out of New Zealand compared to Palmdale. The time improvement for FORCAST is 15-20% for most observations. Even greater differences of

50-75% for FIFI-LS and GREAT observations of spectral lines (e.g., [O III]) near telluric water lines are possible.

To account for the impact of large seasonal variations in water vapor on allocated integration time, SOFIA will make two major changes. The first is to change the scheduling software to account for the north-south differences in integration time and to plan the flights accordingly. With the increased Southern Hemisphere opportunities, this improved efficiency will be easily realized. The second initiative under development is to allow changing the order of flights in a flight series depending on the forecast water vapor overburden and potential thunderstorm activity en route. The ability to create accurate water vapor forecast maps along with thunderstorm activity predictions with up to 72-hour lead times has been implemented. Users can tag observations that are highly dependent on water vapor overburden in their observation requests. At the 36-hour weather update for a scheduled flight, if the flight plan includes tagged observations and high water vapor overburdens or thunderstorms are forecast, that flight plan can be swapped with another from later in the series to avoid potentially poor observing conditions.

5.3.2 More Efficient Instrument Modes

Several improvements to instrumentation that are presently in development will also yield more science per flight, including the newly offered HAWC+ scanning polarization mode and FIFI-LS On-The-Fly mapping mode. Both have been offered on a shared risk basis in Cycle 9 and will be fully implemented in Cycle 10. The scanning polarization mode will achieve the same signal-to-noise about 2 times faster than the previous chop-nod observing technique for HAWC+. The On-The-Fly mapping mode will achieve the same signal-to-noise 1.3-2.5 times faster for FIFI-LS observations.

5.3.3 New Software Automation Initiatives

In the last three years, SOFIA has implemented a series of software automations that saves hours of labor per flight and increases reliability, consistency, and accuracy of the mission operations tools. These improvements have also allowed the mission to reduce operations staff and add research staff and postdoc positions, fostering a more science-driven culture. Efficiencies, in some cases as high as 100% to 1000%, were gained across all observatory functions: pre-flight (automated flight planning and mission preparation tools), in-flight (telescope- and instrument-operator tools that boost efficiency and allow single operator control), and post-flight (automated metrics gathering).

SOFIA is embarking on the next wave of innovative automation. Examples of planned improvements include full-frame tracking that eliminates manual setup on targets and increases reliability and efficiency of observing, increased interoperability between the

integration-time calculator and the observation-request software, improved automatic observation duplication checking, and streamlining the creation of SOFIA grants. Additional time-saving improvements will be made to the flight scheduling software, observation preparation tools, and the data pipeline.

5.4 Prioritize Legacy Programs

SOFIA's Legacy programs (§3.2) are available to the public immediately and enrich the value of the archive for users beyond the original teams. Facilities like Hubble, Spitzer, and Herschel have shown that larger programs like these increase the science productivity of the observatory and lead to higher-impact publications [Apai et al. 2010].

SOFIA has substantially increased its investment in Legacy programs by raising the share of research hours to 30%. SOFIA expects to have at least nine Legacy programs completed by the end of FY25, substantially enriching the archive value and utility.

One Legacy program, the mid-IR Galactic Center Mapping Survey, is already complete with a first publication [Hankins et al. 2020]. In spite of delays brought on by COVID-19, SOFIA has prioritized the scheduling of Legacy programs and expects to complete four more by the end of FY23: Magnetic Fields in Galaxies (§2.1.4), HyGAL (§2.1.3), FEEDBACK (§2.1.1), and FIELDMAPS (§2.1.2). SOFIA has accepted an additional four pilot-phase Legacy programs: the Joint Legacy Survey of [CII] in the LMC (PI: Madden), A Two-Color Polarimetric Survey of the Galactic Center (PI: Chuss), the Study of Interstellar Magnetic Polarization: A Legacy Investigation of Filaments (PI: Pillai), and Mapping the 6 Micron Molecular Water Line Across the Lunar Surface (PI: Lucey). Each of these programs will have to demonstrate both technical and scientific feasibility before being promoted to full Legacy status.

5.5 Develop Far-IR Time Domain

Astro2020 emphasizes the importance of time-domain astronomy for their New Messengers and New Physics science theme. SOFIA has demonstrated the scientific benefits of time-domain studies (§2.3) with FORCAST, HAWC+, and FIFI-LS. Far-IR satellite missions have lifetimes less than five years — a limit imposed by the exhaustion of onboard cryogenics. SOFIA has a design lifetime of 20 years, allowing unique, continuous access to the far-IR skies that opened this waveband to time-domain studies. Our objective over the next three years is to develop time-domain science cases and techniques for the IR/far-IR that can address these important science objectives of Astro2020.

Starting in Cycle 10, SOFIA will be offering a new sub-category of programs called Multi-Cycle Target Monitoring programs, where proposers can request observing time

(<20 hours per cycle) for up to three cycles. In addition, astronomers can use the Cycle 10 submission to propose observing ideas for a potential supernova in the Milky Way or Magellanic Clouds. Successful proposers will be invited to form a supernova team that develops a comprehensive observing program strategy where all data will be made public immediately.

The field of time-domain observations in the far-IR is so new that astronomers are only just beginning to realize its scientific potential. SOFIA will hold a workshop on time-domain astronomy for the IR/far-IR/sub-mm where the community can discuss current results, brainstorm on new ideas, and develop observing strategies that can maximize science return from SOFIA. Experts from the multi-messenger, gravitational wave, Nancy Grace Roman Telescope, and Vera Rubin Telescope communities will be invited in order to cast a wide net for science ideas.

5.6 New Science Instrumentation

Increase Science Discovery Space

For at least the next decade, SOFIA will be the only facility that provides regular access to the far-IR sky. Unlike space missions, SOFIA can repair, upgrade, and replace its instruments as science priorities evolve and technologies improve. This continual development allows SOFIA to outperform and significantly extend the legacies of previous instruments and prepare the groundwork for new missions. The SOFIA Instrument Roadmap³, released in March 2021, presents a community-driven plan to expand SOFIA's discovery space (Figure 5-4) and enable impactful Legacy programs. The three-step plan described below will not only increase science return but also provide crucial opportunities for astronomers to develop sophisticated instruments that set the stage for the future space missions recommended by Astro2020. In parallel with these efforts, the German partnership of SOFIA has been formulating their contributions for future instrumentation. The outcome of this process will be merged with the goals of the Roadmap outlined below.

5.6.1 Step 1: HAWC+ Upgrade

One of the most desirable capabilities of SOFIA, in support of the Astro2020 science, is the unique ability to map magnetic fields at the peak of the thermal Spectral Energy Distribution (SED). There is a strong desire by the astronomical community to study magnetic fields in fainter Galactic regions and external galaxies, as well as map magnetic fields at high resolution over larger swaths of the sky. For example, a potential Legacy program was formulated out of the community workshops that would utilize a more efficient polarimetric mode on SOFIA to map the magnetic fields of molecular clouds in the Gould Belt on scales

³ <https://www.sofia.usra.edu/instrument-roadmap>

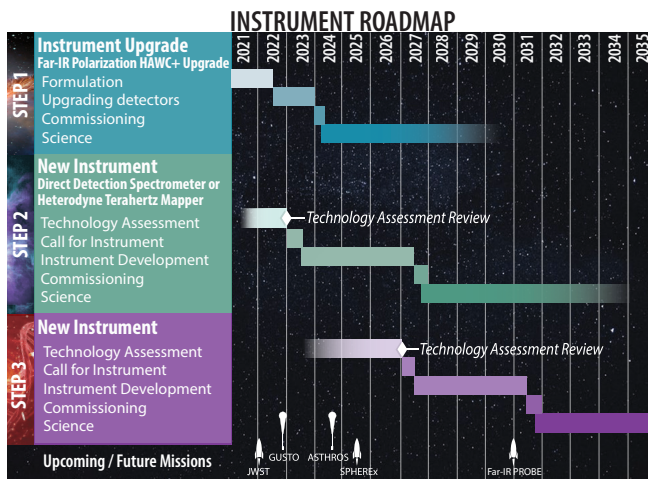


Figure 5-4 Instrument Roadmap for SOFIA has three steps with this notional, success oriented timeline. Implementation of Step 1 has started.

from collapsing clouds to the protostellar cores. Such a polarization survey at wavelengths close to the thermal dust peak ($\sim 200 \mu\text{m}$) could map magnetic fields below the critical column-density threshold for star formation ($A_V = 7 \text{ mag}$). For the brightest regions, shallower observations at shorter wavelengths ($\sim 60\text{-}100 \mu\text{m}$) would detect the warm protostellar envelopes of the densest cores and trace the magnetic fields down to protostellar scales. These observations will allow, for the first time, a comprehensive statistical comparison of well-resolved observations with state-of-the-art MHD simulations of clouds and cores.

To realize programs such as this with achievable amounts of telescope time, SOFIA would need a polarimeter with a mapping speed four times faster than presently available with HAWC+. This can be achieved through the first step of the Roadmap to upgrade HAWC+ with new detectors in the next two years. This polarimetric capability would enable the Gould's Belt survey with <150 hours of observing time. SOFIA has commenced Step 1 by funding independent far-IR detector development groups to formulate proposals for the upgrade with either transition-edge sensors (TEs) or kinetic inductance detectors (KIDs). The proposals will be evaluated in summer 2022 and their selection will be based on effectiveness of the new detector systems, as well as the cost and schedule of the upgrade with expectation that it is finished in FY24. If a HAWC+ upgrade is not cost-effective, then the HAWC+ instrument will continue in its current productive state, and SOFIA will move more quickly on to Step 2.

5.6.2 Step 2: New instrument: Direct Detection Spectrometer or Terahertz Mapper

The second step of the Roadmap is a new instrument for which there are two scientifically motivated concepts: a Direct Detection Spectrometer and a Heterodyne Terahertz Mapper.

The astronomical community expressed keen interest in the study of the formation, chemical composition, and evolution of planet-forming disks via the Astro2020 report and the Roadmap workshops. The most critical parameters required in planet-formation models are the total amount of gas in a disk and the amount of water in both solid and liquid forms, both of which are best determined using far-IR spectroscopy. SOFIA could measure the molecular hydrogen, the most abundant gas in the disks, by detecting the ground-state HD rotational line at $112 \mu\text{m}$. With access to the many strong water lines in the $20\text{-}120 \mu\text{m}$ band, SOFIA could also measure the amount of water in the planet-forming zone and trace the location of the snow line, where H_2O transitions from predominantly solid to vapor form. This science would require high-resolution spectroscopy ($R \sim 100,000$) from ~ 30 to $125 \mu\text{m}$ in order to determine the kinematics of these lines. The Roadmap identifies a Direct Detection Spectrometer to provide this new capability to the community. The instrument could be available within the next six years.

Alternatively, several ambitious programs with high scientific and Legacy value that address the Astro2020 theme of cosmic ecosystems have been identified by the community: (1) observations of the 100 brightest Galactic star-forming regions to form a comprehensive catalog of [C II] and [O I] maps, (2) creation of a complete [C II] and [O I] map of the Galaxy's entire Central Molecular Zone, and (3) high spectral resolution [C II] and [O I] mapping of ~ 50 nearby galaxies. Such observations would provide a wealth of data to the SOFIA archive that could be mined for decades to come.

To accomplish these programs, SOFIA would need to improve on the seven-pixel GREAT instrument by an order of magnitude. This would allow faster mapping of larger areas, enabling more efficient operations. The Roadmap identified a 100-pixel Heterodyne Terahertz Mapper to meet these scientific objectives that could be available in the next six years. Given the strong demand to perform science using [C II] and [O I] mapping observations, SOFIA is looking at ways to minimize the time between the end of GREAT's tenure and the arrival of a 100-pixel Heterodyne Terahertz Mapper.

A technology readiness assessment in 2022 will determine which type of instrument will be developed for Step 2. The direct detection spectrometer technology is being advanced through APRA and SAT and is aligned with the Astro2020 mission architecture maturation programs. Heterodyne technologies are being advanced by ALMA and the balloon program. After the technology readiness review, a call will be issued to select the team to build and deliver an instrument to the SOFIA Project by FY27.

5.6.3 Step 3: Future Instrument for 2030s

Looking beyond the six-year time horizon, Step 3 of the Roadmap is expected to be a call for a new instrument that would be delivered in 2031 and available for observations in 2032. The scientific and technical landscape will have significantly changed by that time, so SOFIA will hold a new workshop to gather community input to guide Step 3.

5.7 Performance: Demand, Productivity, and Impact

SOFIA's timeline for success is quite different from that of a typical space-based mission. Where space missions have high launch costs and expendable cryogen supplies, operations are relatively inexpensive. SOFIA, on the other hand, had zero launch costs and replaceable cryogenes, but operations include aircraft maintenance, fuel, and crew (Figure 7-4). As an airborne rather than a space-based observatory, SOFIA also has less time per year on the sky. These factors were built into the SOFIA design model from the beginning. It included a slow ramp up toward scientific success, which was compensated for by the long mission lifetime made possible by replaceable cryogenes. Judging SOFIA by the space-based mission model sets inappropriate expectations for its science productivity. Similarly, if space missions were judged by the airborne model, they would never get off the ground.

Implementing the FMR recommendations (§4), new initiatives (§5), and innovative efficiencies based on experience with aircraft operations have set SOFIA on a trajectory to reach its full scientific potential. SOFIA achieved full operational capability in February 2014. The demand for SOFIA has increased steadily (Figure 5-5) with resulting oversubscription rates between four and five. Legacy programs are partly responsible for these increases. Adding observing hours, growing

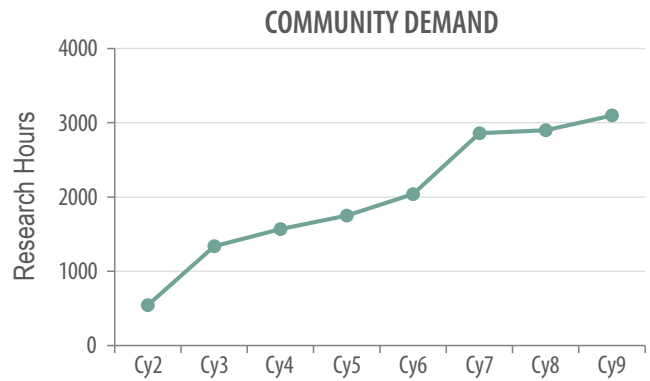


Figure 5-5 Demand for SOFIA time from US Queue proposals has grown steadily since Cycle 2 when SOFIA achieved full operations.

the SOFIA community, and giving all instruments an opportunity to observe in the Southern Hemisphere are expected to increase demand for SOFIA.

SOFIA's peer review science publications based on observations (GO and GTO) and archives (archival data and theory) have steadily increased since 2014, with a doubling in annual publication rates over the last three years (Figure 5-6). SOFIA is currently at an inflection point of its growth in science publications, similar in gradient to the early years for space missions. Technical publications (81) are almost one third of the science publications (281), which demonstrates the value of SOFIA to the astronomical community in far-IR technology and instrument development. Including the technical papers, SOFIA has a total of 362 publications, in line with the expectations of the airborne model discussed above. Projections indicate that SOFIA will reach over 100 publications per year by 2024.

The PMOs described here are designed to amplify the rate of SOFIA publications (Figure 5-6). The increased number of flights per year (PMO 1) and the archival growth from the accumulated observations (PMO 4) are the primary drivers. Added efficiencies (PMO 3) and community growth (PMO 2) are secondary drivers.

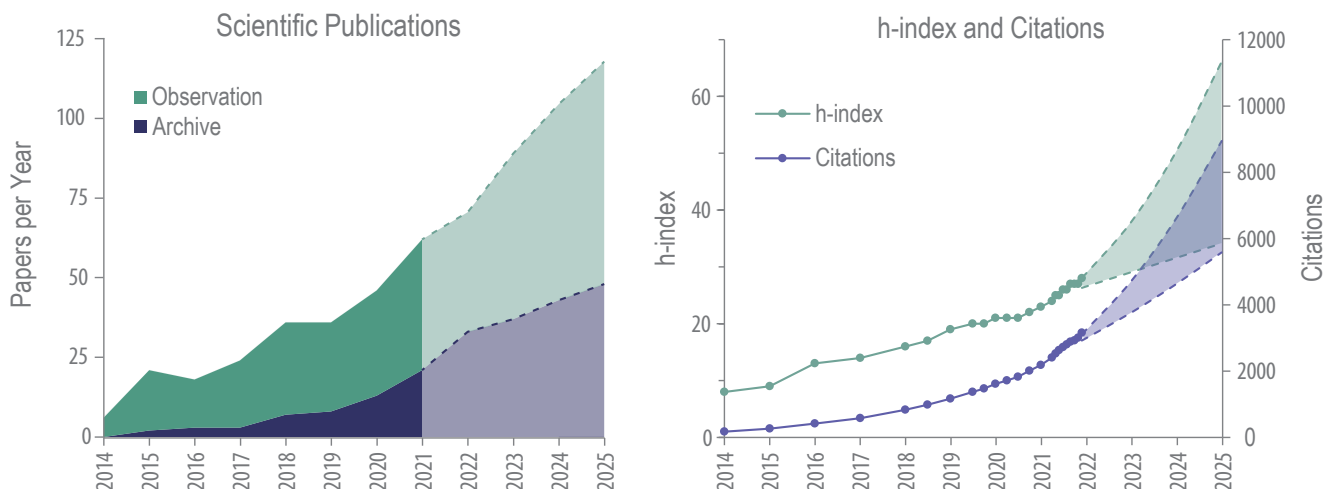


Figure 5-6 Annual publications (left) and citations (right) have been growing since full operations in 2014. SOFIA's intentional, programmatic changes will significantly increase science productivity in future years.

The predictions in [Figure 5-6](#) incorporate a distribution of time lags from observations to publication.

- Increased observing time ([§5.1](#)): +50%;
- Increased Southern Hemisphere observing time ([§5.1](#)): +100%;
- Efficiency of Northern and Southern Hemisphere observations ([§5.3.2](#)): +10%;
- Efficiency due to better water vapor conditions in Southern Hemisphere ([§5.3.1](#)): +15%;
- Hiring SOFIA postdocs in FY21 and FY22 ([§5.2.1](#)): +8 papers per year;
- Increase archive size ([§5.4](#)): +15% per year;
- SOFIA Archival Research Program Call ([§3.2](#)): +10 papers per year

These predicted publication values can be considered a conservative lower limit on improvement because science outreach initiatives that will grow SOFIA's community ([PMO 2](#); [§3.5](#), [§5.2](#)) are also expected to increase publication rate and impact, but those values are hard to quantify.

SOFIA's scientific impact ([Figure 5-6](#)), as reflected in the h-index (28) and citations (3152), demonstrates its growing influence. Including technical papers, the h-index (33) and citations (4784) both rise, demonstrating the importance of the SOFIA instrumentation program and its support of the Astro2020 recommendation for a future far-IR probe and Great Observatory missions. Future h-index and citation extrapolations predict substantial increases over the next few years. Extrapolations from a fit to the entire history of SOFIA h-index and citations define the conservative lower limits that are flattened by the earliest years. The upper limits extrapolate trends from the past two years into the future and show a non-linear rise. We expect that SOFIA's investment in community outreach through virtual workshops, conferences, and training schools will continue to enhance h-index and citation rates.

Comparison of SOFIA's scientific productivity with other NASA missions must be done with care. SOFIA is a suborbital platform, a crewed mission, the only airborne observatory for astrophysics in the world, and the only far-IR observatory available to the astronomical community. SOFIA's science publications (281) are significantly higher than the science return from far-IR balloon programs (8). SOFIA has been compared to Hubble, a mature robotic space mission (~30 years) with a substantial archive. A better comparison is with Herschel, a recent far-IR mission that provided 22,000 observing hours and produced 900 publications. SOFIA has observed for 4000 hours and produced 281 science publications. SOFIA has already passed Herschel in paper-writing efficiency, and over its operational lifetime, SOFIA will provide a similar number of observing hours and publications.



6. OBSERVATORY OPERATIONS

SOFIA is a highly integrated observatory, with the aircraft, telescope, science instruments, mission systems, and ground systems working in concert to conduct science and mission operations. Presently all observatory components are healthy and functional. This section describes the operations, maintenance, health, and safety of the observatory. It incorporates changes and initiatives following the recommendations of the standalone aircraft operations and maintenance review conducted in 2019 prior to the FMR.

SOFIA is staffed to fly four 10-hour flights per week, typically Monday through Thursday with a Friday contingency. SOFIA has successfully flown 630+ science flights to date. Mission teams work around the clock to support flying science missions as well as to perform maintenance. The day shift prepares the observatory for the flight, the evening crew launches the aircraft and operates the observatory, and the weekend team fixes maintenance issues, works on routine maintenance, and performs instrument changes. The observatory operates out of Armstrong Flight Research Center (AFRC) in Palmdale, California but also deploys annually to Southern Hemisphere sites, typically Christchurch, New Zealand.

6.1 A Day in the Life of SOFIA

Each member of the ground, science, and flight crews contributes to collecting science and delivering it to the observer. The flight crew consists of two pilots and a flight engineer, and the science mission crew requires at least five: a mission director, a telescope operator, a science instrument operator, an instrument scientist, and a safety technician. Behind the scenes, the science mission and flight crews are supported by a ground crew in four specialized areas:

- Science Operations manages operational aspects related to the science data collection, including scheduling, flight planning, in-flight data collection, data reduction, and quality checks.
- Mission Operations (MOPS) comprises telescope operators, instrument operators, and mission directors. Following NASA guidelines, MOPS sets the processes and procedures for safe and efficient use of the observatory to enable science data collection.
- Engineering and Maintenance encompasses the tasks associated with maintaining the observatory and incorporating aircraft and science system upgrades, as well as planning for and maintaining the general

health of the observatory and its components. DLR maintains the Telescope Assembly.

➤ Aircraft Operations includes the flight crew that will fly the aircraft and prepare and file the flight plan based on the science observing plan.

Starting two days prior to a given flight, Science Operations supplies the observing plan, which navigators convert to an “aviation flight plan” providing language and data points compatible with the national airspace system. At 36 hours before the flight, navigators review airspace constraints (such as restricted operating areas, other airports, and international boundaries) and how the forecast winds aloft would impact the planned flight path. The science flight plan may then be adjusted and reprocessed before being filed with air traffic control. To keep the science observations on schedule, the flight crew is required to pass each waypoint within two minutes of the planned time.

Day of Flight – 24-hour Cycle

A day in the life of SOFIA is illustrated in Figure 6-1 and described below in detail.

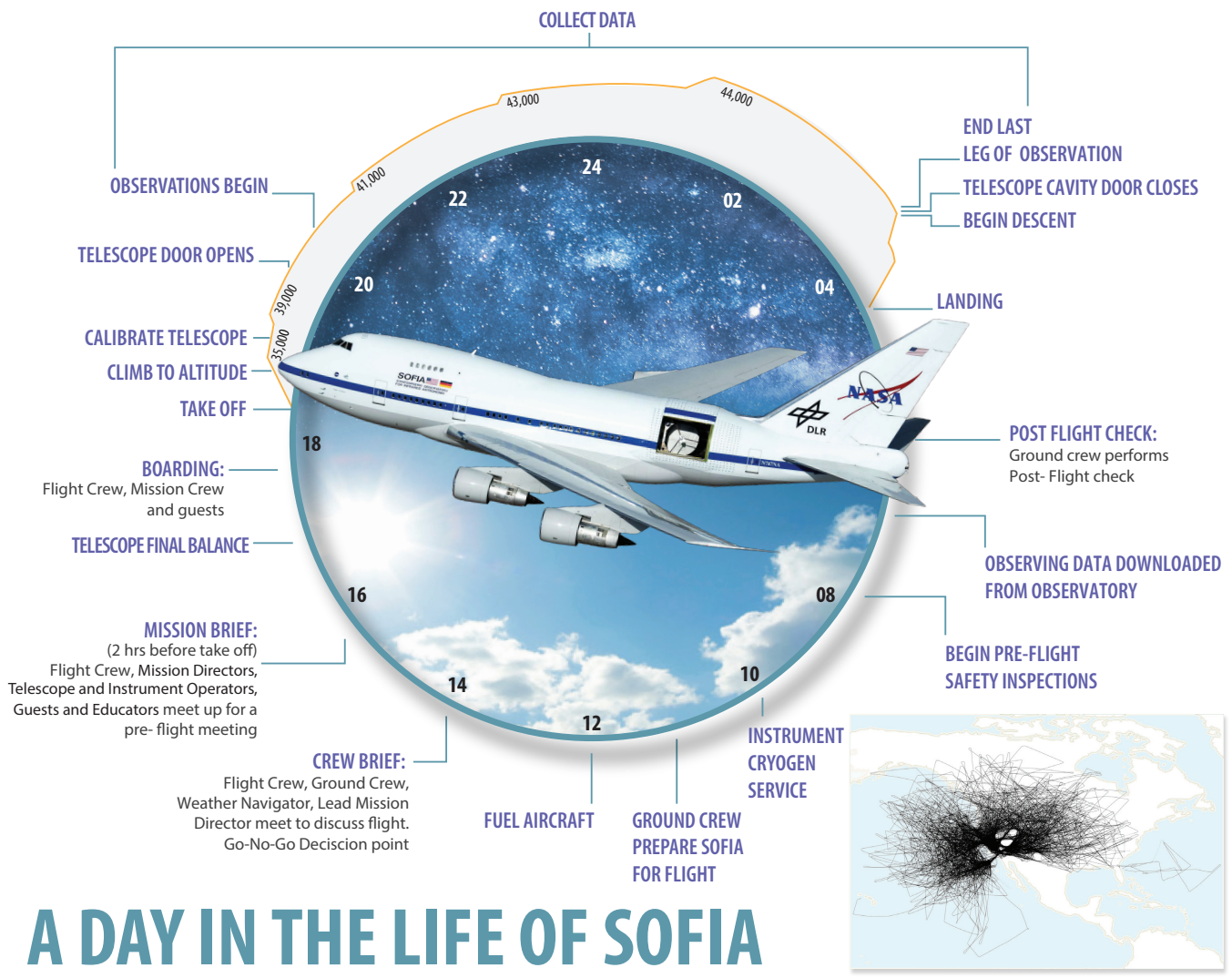
4 a.m. – The Sun is not yet on the horizon

✦ SOFIA typically lands at approximately 5 a.m., depending mostly on the local sunrise. One hour prior to landing, maintenance personnel arrive to prepare to receive the observatory. A visual inspection of the ramp area and runway is conducted for safe landing and taxi.

5 a.m. to 6 a.m. – After landing

✦ The maintenance team connects servicing carts to power and cool the aircraft and the telescope cavity environmental system to prevent moisture build-up in the optics and electronics.

✦ The flight crew reports any aircraft discrepancies to the maintenance team. These are recorded in the NASA Aircraft Management Information System.



A DAY IN THE LIFE OF SOFIA

Figure 6-1 A day in the life of SOFIA operations showing the events that need to be accomplished for safe and successful execution of scientific observations. The operations team has mastered this timeline and is able to efficiently troubleshoot most of the technical issues to maintain this cycle for a timely take-off. The inset box shows the Northern Hemisphere portion of SOFIA's 630+ science flight paths successfully flown and executed to date.

- ✦ Science and mission operations teams write up their post-observing reports.

7 a.m. – Data transfer and the start of the day

- ✦ Technicians transfer data collected from the previous night's mission and send them to the Science Operations team at NASA Ames for processing.
- ✦ Postflight checklists and external inspections of the airframe and wheels are conducted to ensure no damage occurred during the flight.
- ✦ Avionics and mechanic technicians perform systems checks and service checks and configure the aircraft cockpit and mission systems for the next flight.
- ✦ Science instrument cryogen service is performed by the MOPS team.

2 p.m. – Coordination of the night's flight

- ✦ During the day-of-flight tag-up at 2 p.m., the mechanics, avionics technicians, MOPS staff, DSI telescope maintainers, and day shift Mission Director brief the status of all systems to quickly identify any issues that might prevent that evening's flight.
- ✦ MOPS team begins preparing the mission systems, uploading the files required for the night's observations, and configuring the displays for the Mission Director and Telescope Operator.
- ✦ After shift changeover, mechanics and avionics technicians complete the aircraft and avionics, mission systems, and instrumentation preflight checks.
- ✦ All of the preflight inspections feed into the Flight Preparedness Report (FPR), a master document which verifies that the aircraft and mission systems are ready for flight. The FPR is then brought to the Crew Brief where it is reviewed and discussed by the flight crew, then signed off by the pilot, operations engineer, and the aircraft's crew chief.

6 p.m. – Pre-flight briefings

- ✦ Crew Brief: mechanics, avionics, operations engineers, flight crew, and science mission crew representatives meet to discuss safety of flight items, aircraft status, the flight route's planned weather, landing constraints, and alternate airfields. This is the major go/no-go decision point.
- ✦ Following the Crew Brief, the aircraft's flight engineer starts the preflight checks while the remainder of the staff attends the Mission Briefing.
- ✦ The Mission Briefing presents information from the Crew Brief, on a higher level, to the science mission staff who will be on board the flight. This meeting

"I was in the cockpit of a flying NASA observatory, speeding south through the Antarctic stratosphere. The aurora were arcing and dancing around us. In the back of the plane, a telescope was preparing to point at a star of my choosing, gathering data that would help me unravel one of the many mysteries of the Universe that I'd dedicated my life to exploring."



Prof. Emily Levesque (Univ. of Washington), "The Last Stargazers" Sourcebooks, 2020

also gives the science mission staff the opportunity to present the night's science observing plan to the flight crew. Guest Observers on the night's flight can present a short overview of the science that will be collected; this is an opportunity for them to interact with the mission team. Any journalists and educators flying on the mission are also introduced.

8 p.m. – Take off into the night sky

- ✦ Following the Mission Briefing, the night's crew boards the observatory. The flight crew completes their checks, then taxis into position at the end of the runway.

To observe the first target of the night, SOFIA must take off at the exact planned departure time. Approximately 40 seconds before takeoff, the pilots will advance the engine throttles that push the nearly 690,000-pound, fully loaded flying observatory into the sky. Ten hours later, the observatory will land and the process begins again.

Observing the Infrared Universe – On Board SOFIA

The observatory flies a stepped profile, first climbing above 35,000 feet where it levels off and the telescope's upper rigid door is opened to allow the telescope to adjust to the ambient outside air temperature. As the observatory burns fuel and becomes lighter, it climbs higher. The first observing period typically begins at 39,000 feet and steps up to 41,000 feet, then later to 43,000 feet. SOFIA's maximum observing altitude is 45,000 feet, which is only accessed at the end of the flight.

Every flight requires multiple Science and Mission Operations personnel working together with the pilots and navigators as a team. Mission Directors oversee and coordinate all activities on the main deck. They maintain communications with the flight deck, coordinating with the pilots the handoffs between flight deck activities (ascents, descents, and turns) and main deck activities (door, telescope, mission systems, science instruments, and educator engagement). The Mission Directors control the flight plans and update them when required, communicating any changes to the flight crew. The Telescope Operators take charge of the telescope when the flight crew reports the aircraft is on heading for a science leg. Once it is complete, the Mission Director reports to the flight crew that they are ready to turn to the next leg. Telescope Operators monitor and control the telescope, including all pointing, focusing, chop-nodding, dithering, and scanning. Instrument Scientists, with the help of an Instrument Operator,

control the science instrument with prepared observing scripts and run quick data reductions in flight to ensure that the data being taken are of sufficient quality.

6.2 Dedication to Safety

The SOFIA team is dedicated to performing operations in the safest manner possible. A team of inspectors perform preflight and postflight inspections to ensure the aircraft is safe to fly. In addition, they oversee the maintenance team to ensure all tasks are performed to the highest standard. All maintenance records for SOFIA are in the NASA Aircraft Management Information System. This electronic workbook tracks all maintenance and alerts the team when maintenance is due. Inspectors work in this system to ensure that no maintenance item is missed and the aircraft is safe to operate.

As SOFIA is a crewed mission, human health and safety are also key aspects of the overall safety of the observatory. Serving as a crew member on board SOFIA entails a great deal of nighttime work with the potential for both acute and chronic sleep loss, as well as circadian rhythm dysfunction. Fatigue can result in decreased performance with an increased risk of operator error. Safety and fatigue considerations drive the observatory's staffing requirements, which are detailed in preexisting and proven regulations.

NASA AFRC manages fatigue risk for SOFIA through a layered approach that includes education and training of SOFIA staff, work schedule scoring, obtained sleep metrics, workplace and operational mitigations, and, should a mishap occur, incident or accident investigation. Safety of staff and the observatory are at the forefront of all aspects of the SOFIA mission.

6.3 Operations and Health of the Observatory

Platform – Aircraft

The SOFIA aircraft is, in aviation maintenance terms, “young” for a 747. Most 747s that spend their lives in commercial service accumulate between 90,000 and 100,000 flight hours, while SOFIA has flown less than 45,000 hours. Another indication of an aircraft's service life is the number of “cycles” it has accumulated. A cycle is one takeoff and one landing. Typical 747s will have logged more than 45,000 cycles, while SOFIA has yet to pass the 15,000 mark. The observatory platform's history of low utilization during its airline career gives it more than enough life for its planned 20-year life span.

Many aircraft components must be replaced at specified intervals determined by either calendar time, flight hours, or cycles. Engines fall into the flight hours or cycles category and the majority of engines on the wing and in storage have, on average, approximately 44 years of flight time remaining. Acquiring newer engines is part of the mission's effort to increase

dispatch reliability rates. In the past six years, 54 flights (~440 research hours) were canceled due to downtime needed to fix engine issues. By having spare engines available, faulty engines can be swapped out quickly and fixed later. In Fall 2021, SOFIA was able to acquire six serviceable engines (as well as a spare auxiliary power unit) from two recently retired 747SPs. With these acquisitions, the project now has more than enough spare engines to have replacements at the ready, as well as carry SOFIA through its remaining operational life.

SOFIA is committed to keeping repair downtime to a minimum by maintaining expertise and replacement parts. SOFIA's maintenance team is part of the 747SP operators users group which meets quarterly to discuss aircraft issues and solutions to accessing parts or specialized tooling. SOFIA has also contracted with Boeing Aircraft On Ground (AOG) Services to provide original equipment manufacturer technical expertise for various aspects of repair support. In the past, Boeing AOG technicians have been used to chase difficult-to-locate fuel seepage from the wing/engine pylon junction. This contract is ongoing and provides 24/7 support when needed, thereby increasing the reliability of the observatory and minimizing maintenance downtime. By having an extensive inventory of in-house parts, SOFIA can be maintained well within the life of the project. For those parts that are not in-house, the Armstrong Aircraft Parts Office works closely with Boeing, other 747SP operators, and key parts suppliers to ensure that all parts for SOFIA are readily available when needed.

Telescope

SOFIA's high-performance telescope was designed and engineered by DLR and is the largest telescope to ever be integrated into an aircraft. The telescope floats within a hydrostatic bearing and maintains pointing on a target by employing gyro stabilization like a satellite telescope. During flight the upper rigid door of the telescope is pulled back, exposing the telescope to the low temperatures and pressures of the stratosphere. Since the foundation of the telescope is a moving 747 aircraft, it is subject to aircraft vibrations, turbulence, and wind-driven oscillations. Through highly specialized and of sophisticated design, the telescope overcomes all these issues to provide scientific data that is diffraction-limited beyond wavelengths of 25 μm . Over the span of more than 500 successful science flights, the telescope has proven to be extremely reliable. During the past five years (2017 to 2021) only six flights were lost due to telescope issues.

The German SOFIA Institute (DSI), subcontracted by DLR, operates and maintains the telescope. The DSI workforce performs daily maintenance, ensures operational readiness, and conducts periodic inspections

between flights or over the weekend to keep the telescope operating optimally. Maintenance tasks that require an extended amount of time and effort are scheduled during the dedicated annual maintenance period. DSI also generates spare parts/systems for the telescope, including obsolescence upgrades. The telescope's software and hardware are regularly upgraded to optimize its performance without interfering with the observation schedules. Regular improvements range from operational and efficiency improvements to entirely new observations modes or features such as Lissajous scanning.

One area of continual improvement is in motion compensation of the telescope, with the goal of providing incrementally superior image quality. For instance, improvements have been made to the highly complex secondary mirror control mechanism, eliminating resonances that negatively affected image quality. Planned improvements to image quality in the next two years will also come through enhanced flexible body compensation for the many bending modes the telescope undergoes in flight and installation of an active damping system, as well as further improvements to the secondary mirror control mechanism. With an anticipated image size improvement of at least 10% from the active damping system alone, SOFIA will be able to reach the diffraction limit at wavelengths even shorter than 25 μm .

DSI has procured two new optical imagers with a factor of five higher quantum efficiency and two to three orders of magnitude lower dark current than the present Wide Field Imager and Fine Field Imager cameras that are used for target acquisition and tracking. In combination, the new cameras will significantly increase the number of usable guide stars on any given star field. The new imagers will also greatly enhance the planned implementation of "full-frame tracking" mode, which will eliminate many of the manual setup tasks for the telescope operators and increase reliability and efficiency of the observations. These upgraded cameras will be installed in 2022.

6.4 Science Instruments

Mission operations personnel, often along with instrument scientists, begin to prepare an instrument for installation on the telescope about four weeks prior to its use. This begins with warm functional checks, vacuum pumping and cryogenic cool-down, and cold functional checks of the detectors, motors, and electronics. Depending on the instrument, optical alignment may be necessary using the Telescope Assembly Alignment Simulator (TAAS). Although instruments currently operate serially, SOFIA is studying a backup instrument plan with associated flight plans ready should a scheduled instrument fail.

Installing a science instrument onto SOFIA's telescope requires significant coordination with the aircraft maintenance team. What used to be a very time-consuming affair during the prime mission now occurs in one to two days and is scheduled over the weekend to not impact flight opportunities. After installation, full functional checkouts of the instrument and telescope are conducted to insure they are properly mated and communicating with each other. Occasionally, non-routine instrument tests or alignments that cannot be done in the lab or on the TAAS will need to be performed on "line operations," where the aircraft is towed out of the hangar at night and the observatory is utilized while on the ground.

All facility science instruments are currently healthy and operational. Regular maintenance of instruments also includes improvements to enhance performance or efficiency. Select examples are:

HAWC+

The mission added the capability to observe at 63 μm ; improved its adiabatic demagnetization refrigerator's performance by 35%, allowing greater flexibility in mission operations; enhanced data storage by replacing the original hard drives with 4 TB solid state drives; and improved ruggedization via newly designed and manufactured protective structures to prevent damage to the instrument while being shipped to deployment sites.

FIFI-LS

A new on-the-fly mapping mode increases observing efficiency and enhancement of the blue channel signal. The instrument's preparation time has also been reduced by 25%. Under consideration is an update to its operating system as well as replacement of the electronics in the instrument rack and the counterweight rack.

FORCAST

Recently a spare instrument computer was built that can serve as a replacement for either of the existing two computers in the event of failure. Future enhancements to FORCAST would include updating the computer hardware and operating system.

EXES

The entrance window was recently replaced. The new window has 60%-70% lower emissivity, depending on wavelength, and has a more durable protective coating. The active damping system will primarily benefit EXES by reducing image size and exposure time by at least 10%.

6.5 Mission Systems

SOFIA Mission Systems include the Mission Controls and Communication System (MCCS), the telescope Cavity Environmental Control System (CECS), and the telescope Cavity Door Drive System (CDDS). The MCCS provides mission communication, power distribution,

data acquisition, data archiving network services, and Observatory crew interfaces.

When SOFIA achieved Full Operational Capability (FOC) in 2014, optimizing observatory and mission systems for science observations became a primary goal. The mission implemented many improvements based on the experience operating the observatory during the prime mission period from 2014 to 2019. During this period, critical spares for all observatory systems were acquired to continue operations past the primary mission phase and well into the extended mission phase. As part of the transition to the extended mission phase, staffing reductions were made to the observatory systems engineering team to better align with the group's sustainment strategy. Engineering support now focuses only on the operational support and maintenance of existing observatory systems. Any major systems issues or obsolescence upgrades requiring engineering expertise outside of the current staff would require planning and additional funding to proceed.

Mission Systems Operational Approach

To reduce the impact of a fault/failure in an electrical component, mission systems maintenance has transitioned from a component-level spare part and repair approach to a line-replaceable unit (LRU) approach. This means that if a faulty component is identified in a certain unit, rather than repairing the component, the entire unit is swapped with a spare unit. The faulty unit can then be repaired without schedule impact. An LRU concept also mitigates the risk of delays if a spare part is not in storage or if the spare part is obsolete and can no longer be acquired. Hardware and software maintenance for all Mission Systems is planned to occur during the annual aircraft scheduled maintenance period to minimize impact to observing opportunities.

Example of a Performance-Driven Improvement - Platform Interface Subsystem (PIS)

The PIS is the data processing and control hub for the entire observatory. It collects and processes data from various elements of the observatory and then distributes the processed data to the appropriate subsystem. In early observing cycles, PIS instability was responsible for the majority of lost research hours. The subsystem was completely rewritten with an upgrade that was deployed prior to Cycle 8 (2020). Since that deployment, the PIS has not been responsible for any lost research hours. The upgrade also provided increased science data acquisition efficiency by increasing system throughput by more than an order of magnitude. Science instruments requiring high-frequency positional information can now get that information without missing data or limiting the scope of the data due to system instability concerns. Pointing accuracy of the telescope was also increased by adding parallax, aberration, and refraction

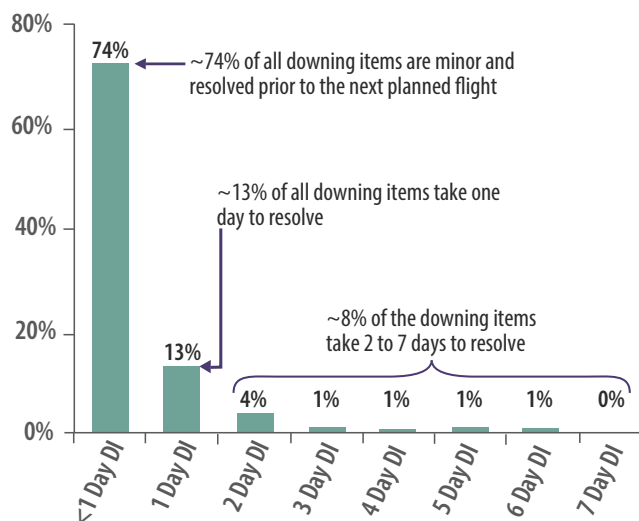


Figure 6-2. Downing items (DI) resolution time between October 2013 and April 2021 are shown here. Most are resolved within a day.

corrections to sky coordinates. The PIS upgrade also led to a small reduction in cost, as the upgrade development team was downsized to fit a sustainment model.

6.6 Downing Items and Resolution

“Downing items” are issues that would ground SOFIA. These can include issues arising from the aircraft, mission systems, telescope, or science instruments, but the majority of them are aircraft-related. About 75% of aircraft-related downing items (Figure 6-2) are minor and can be resolved prior to the next planned flight. Some maintenance issues cannot be addressed in the afternoon prior to a flight, such as engine-related problems, which, on average, are fixed within seven hours. The use of the observatory’s scheduled contingency flight on Friday mitigates the impact of these. Less than 5% of downing items take more than two days to resolve. All SOFIA downing items can be addressed by the in-house team of mechanics and avionics professionals, who have extensive expertise in 747 aircraft systems and maintain a stock of 11,497 different part numbers with 95,239 parts in inventory. In occasional cases, such as fuel leaks, Boeing support is requested.

Downing items impact the dispatch rate, which is defined as the fraction of scheduled flights that take off. The observatory requires a dispatch rate of 80%. The Project strives to achieve 90% by continually improving processes and procedures. For example, engine failures in the past have significantly impacted the dispatch rate. Recently, the aircraft operations group has considerably minimized this impact by reducing the time it takes to swap engines. Non-technical cancellations, such as those due to weather (2-5%), or, more rarely, air traffic control or crew availability, can also impact the dispatch rate. Throughout an

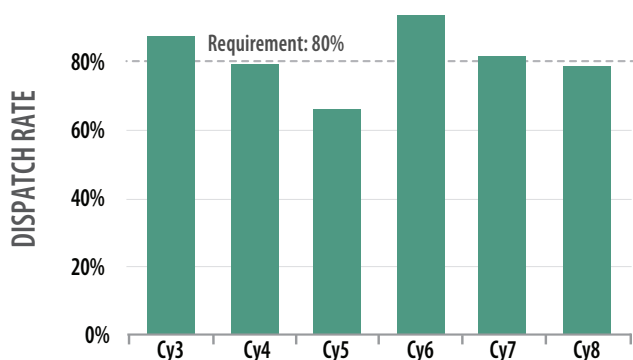


Figure 6-3 Historical observatory dispatch rate as a function of observing cycle.

observing cycle, all flight cancellations and their causes are documented.

Figure 6-3 shows the historical annual dispatch rate that directly impacts the observing time. In some cases, the impact of external factors, such as extended maintenance visits and government shutdowns, requires the mission to re-baseline the remainder of a cycle. For example, the COVID-19 pandemic led to a loss of ~50% of the planned observing hours in Cycle 8. The mission made a significant recovery once the observatory was safely back to operations and completed 45% of the priority 1 and 2 proposals scheduled in Cycle 8.

6.7 Southern Hemisphere Deployments

SOFIA's Southern Hemisphere observations take advantage of the locations (e.g., elevation) of high-priority science targets, longer nights, and low atmospheric water vapor levels during the austral winter. To that end, SOFIA has deployed to Christchurch, New Zealand six times (2013 and 2015-2019; 2020 canceled due to the COVID-19 pandemic). On average, the observatory has flown 24 missions per deployment. While deployed to Christchurch, SOFIA operates from the NSF United States Antarctic Program (USAP) facilities, which are in an "off-season" state during the austral winter. To meet the community's demand for Southern Hemisphere targets, the project is implementing 50 deployed flights from the south annually by adding a series of "short deployments" in April and October, which would bookend the longer 30-flight deployment to Christchurch. Compared to the annual long southern deployment, these short deployments will have a reduced staff and logistics footprint and will operate with some constraints, such as shifting the scheduled maintenance around the deployment. In addition, other Southern Hemisphere deployment sites, closer to SOFIA's operating base in

Southern California, are being established to provide greater flexibility for these short deployments. The operational feasibility of the French Polynesia site has been successfully demonstrated. A site survey for Chile was completed in November 2021.

In addition, starting in the summer of 2021 a modified flight cadence was established for all SOFIA deployments. This compressed cadence of flying four days, two days off, compared to the standard tempo of flying four days, three days off, reduces the time SOFIA team spends away from home, as well as the overall cost of the deployments.

Beginning in 2020-2021, SOFIA had to adapt to the rapidly changing COVID-19 landscape. Knowing that flying from California with our German partners during the pandemic would not be possible, deployment to Germany, where, at the time, COVID rates were much lower, provided a safer working environment. This was creative thinking on the part of the mission team, with the fastest turnaround time ever for organizing a deployment. The Germany-based observations were flown in February 2021, after SOFIA completed its planned extended maintenance visit in Hamburg, Germany. Flying out of the Cologne-Bonn Airport, in close proximity to DLR's headquarters in Bonn and the GREAT instrument's facility at the University of Cologne, the observatory conducted 18 flights over Europe. At the successful conclusion of the deployment, the mission began planning an extended Southern Hemisphere deployment to new deployment site, French Polynesia, in a record turnaround time; Christchurch base was still unavailable in 2021 due to COVID-19. In July 2021, SOFIA successfully conducted science operations from French Polynesia, but unfortunately SOFIA had to return early due to the COVID-19 delta variant surge. The deployment to Chile is being planned for March 2022.

6.8 Technical PMOs

Table 6-1 lists two technical PMOs that will lead to more efficient operations, stronger outreach to the community, and maximized science data collection.

6.8.1 Prepare for Hybrid Remote Operations

Broadband Internet access to SOFIA while in flight could be a game changer, both for observatory operations and for community engagement by scientists and the public. It would also significantly reduce stress on SOFIA staff and pave the path for future efficiencies and cost savings.

Table 6-1: 2022 Technical PRIORITIZED MISSION OBJECTIVES

§6.8.1	Prepare to transition to hybrid-remote operations by implementing faster broadband Internet.
§6.8.2	Maintain observatory dispatch rate at 80% or higher and prevent in-flight science loss.

The current onboard Internet service during flight is provided by an External Observatory Connections System (EOCS) via satellite link. The EOCS has connection speed of ~400 kbps. This very low connection speed is only useful for email, light web browsing, and small file transfers to/from ground-based servers. Because this is a satellite-based system, costs can be as high as \$1,875/ hour, so its use is limited and requires coordination with the Mission Director.

A recent study was undertaken by the SOFIA Project to provide the options for broadband on the observatory as well as to determine preliminary implementation and cost details. The initial indications are encouraging, and the Project anticipates that an infrastructure for new broadband technology from emerging satellite-based systems will be in place over the next few years, which could not only provide higher bandwidth (from 10 Mbps to 1 Gbps) but also virtually eliminate gaps in satellite coverage. The latter would be highly beneficial when SOFIA is on deployments and flying over remote areas. With the fast-changing landscape for broadband access, the vision for hybrid remote operations on SOFIA could be realized by FY24-25. This would mean a reduced mission operations crew, as well as the ability to participate in remote observations by general observers and to conduct in-flight outreach with the public.

The Project will conduct design reviews to kick-start this implementation, which is expected to require modifications to the observatory. Initial cost estimate of upgrading to this type of system starts at a minimum of \$2 million. A new concept of operations will be developed in partnership with DLR and the SMO to assess the benefits and potential cost savings.

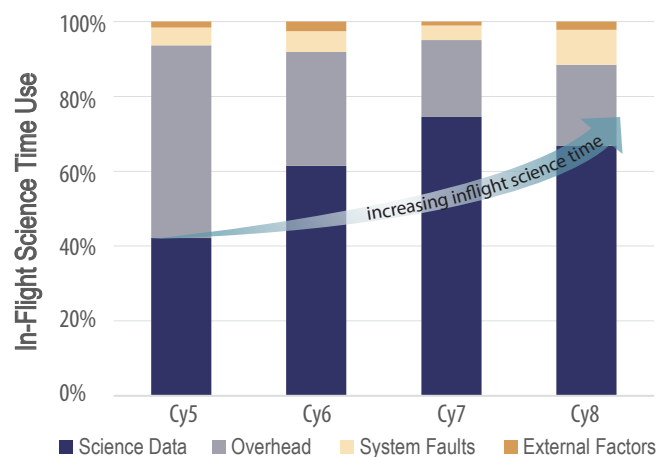


Figure 6-4 Breakdown of in-flight science time use. System faults are time losses due to observatory/instrument issues. External factors are those beyond the control of the project, including weather and Air Traffic Control.

6.8.2 Maintain Observatory Dispatch Rate and Prevent In-Flight Science Loss

The mission must maintain a high dispatch rate by addressing the reliability and obsolescence of the aircraft, mission systems, and science instruments to maximize science data collection and the completion of high-priority programs. Completing observing programs in the same cycle keeps GOs engaged and has the potential to result in faster publication. Details of reliability and obsolescence measures have been covered throughout this section. In addition to maintaining a dispatch rate of >80%, the goal for in-flight loss of science time due to technical issues with telescope operations, instruments, or mission systems is <5% (Figure 6-4). Unlike space missions, SOFIA's ability to observe is impacted by external factors outside the control of the mission, such as weather, government shutdowns, or significant geopolitical situations (e.g., the COVID pandemic). The Project, in collaboration with SMO and DLR, made outstanding efforts in 2020-21 to mitigate the impacts of COVID-19 (§7.3). Efforts to find workarounds to such external factors in a quick, safe, and effective manner will continue in the future.

MANAGEMENT AND BUDGET

7. MANAGEMENT AND BUDGET

7.1 Operating Model and Stewardship

Every aspect of SOFIA's operating model embodies NASA's value of teamwork at its core. It naturally fosters a culture that encourages collaboration in pursuit of common goals as demonstrated by international partnership with DLR and joint NASA center (ARC and AFRC) management (SMD Science Plan⁴ 2.2, 3.1, 3.2). The combined history of these two centers is one of a successful and rich heritage in managing and conducting complex airborne operations. Equipped with exceptionally talented and diverse teams of scientists, engineers, and aviation experts, ARC and AFRC are ideally suited to collaboratively host the SOFIA mission. ARC hosts the SOFIA Project office and the SOFIA Science and Mission Operations Center. AFRC hosts the aircraft operations and has the responsibility for conducting them in a safe and efficient manner. The NASA/DLR cooperative agreement is executed under a formal Memorandum of Understanding. The annual costs of operating SOFIA, as well as the scientific utilization research hours, are shared in an 80/20 proportion that reflects the development contribution of each.

⁴ SMD Science Plan: Innovation, Strategy 2; Interconnectivity & Partnerships, Strategy 3; Inspiration, Strategy 4

The high-level SOFIA organizational structure is shown in (Figure 7-1). The SOFIA Project Office is responsible for the overall management of the mission, which includes the science program, science operations, and mission operations. The Project Manager and Project Scientist work in concert with the two centers and the NASA Astrophysics Division regarding science policy, operations, and governance. They also work collaboratively with their DLR counterparts to ensure smooth and efficient operation of the observatory. NASA-DLR Project leadership solicits community input through the Science and Technology International Council for SOFIA (STICS). The Science and Mission Operations are contracted to the Universities Space Research Association (USRA) and led by the SMO Director, who collaborates with the Project Scientist to solicit community input through the SOFIA Users Group. The SMO Director also works with their German counterpart to issue calls for proposals for the US queue and German queue, respectively.

Decisions on operations and programmatics are driven by the scientific priorities of the mission, which are anchored in recommendations and inputs from various advisory and user committees, as well as science and programmatic reviews (e.g., FMR). The Project has an inclusive decision-making body called the Project Management Board, who discuss in an open forum operations and programmatic topics. This board includes representation from independent safety and engineering technical authorities, science, operations, and DLR. Depending on the magnitude of the decision at hand, the leadership at the two centers and NASA HQ may also be consulted.

SOFIA achieved mature and stable operations towards the later part of the prime mission phase (2014-2019) prior to transitioning to an extended mission phase after the successful 2019 FMR. The project pivoted from maturing observatory systems and optimizing data acquisition to supporting scientific discoveries. Project management focus also made a natural transition from development to increasing scientific productivity, including personnel changes in the science and project management positions.

Building on the successes of earlier SOFIA leaders, the new leadership has demonstrated excellent stewardship by thoughtfully implementing the recommendations of the FMR while lowering the total operating cost from \$85.2M to \$80M. Equipped with a mature observatory, the new SOFIA leadership's priorities and focus have been on substantially increasing scientific return by raising the amount of time spent on large community-driven (Legacy) observing programs to 30%; increasing observing opportunities in both hemispheres by over 30%; introducing standalone archival calls; enhancing

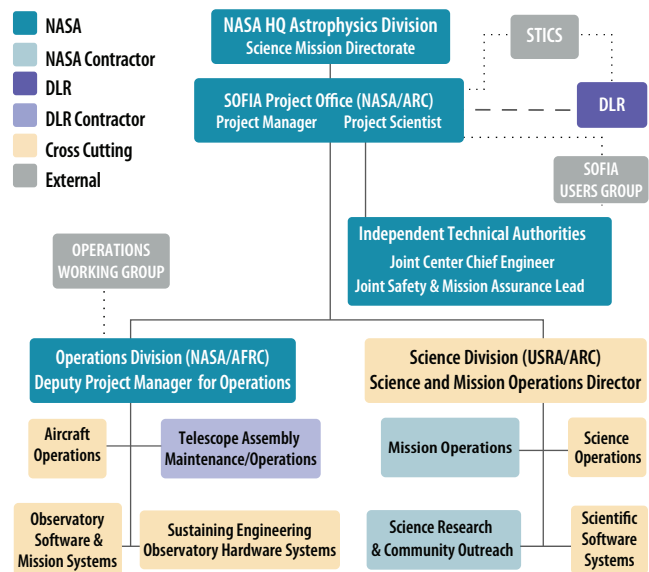


Figure 7-1 SOFIA high-level organization structure.

community engagement and user support to build a strong, diverse, and multidisciplinary science community; raising the minimum level of GO funding from \$10K to \$75K; and creating new opportunities for students from underrepresented groups to pursue their passion in Science, Technology, Engineering, and Mathematics (STEM) (§7.2). SOFIA leadership, with guidance from NASA HQ, developed an instrument roadmap with input from the community (§5.6) to create a path forward for SOFIA to continue to expand its discovery space and support NASA Astrophysics Division and Astro2020 objectives. Dedicated funding of \$5.2M annually has been set aside to support building new instrument capabilities [§2.3, §2.2] that will also foster partnerships with other NASA centers (GSFC and JPL), other federal agencies (e.g., NIST), and academic institutions [§3.1, §3.3]. This effort will ultimately serve the community by providing new capabilities, better science, and higher return on investment.

The quality of the observatory stewardship has been outstanding, as evidenced by numerous initiatives throughout the proposal (§3, §4, §5, & §6), some of which were very challenging and implemented in a short amount of time. The professionalism, creativity, and resilience of the SOFIA team, scientists and engineers, was best demonstrated during the most difficult and challenging phase of the COVID-19 pandemic. The teamwork and the spirit with which they safely conducted two overseas deployments and continued to maximize flights out of Palmdale was a source of inspiration to many at NASA and in the larger science community. It is this spirit of teamwork, adaptability, and perseverance that will continue to drive this mission towards achieving its scientific objectives, making discoveries, and inspiring the next generation of scientists and engineers (§7.2).

Diversity and inclusion are key aspects of the stewardship of the observatory. Many of the observatory positions are designed to specifically support early-career scientists. For example, the Associate and Deputy Project Scientists roles are designed to provide exposure and skill development and have both been recently filled by early- and mid-career scientists. SOFIA demonstrates diversity and inclusion within the organization with half of the project leadership being women, as well as having women supporting every aspect of the mission from communications and community engagement to telescope engineering, instrument operators/scientists, software development, and mission operations. Recent implementation of the dual-anonymous review process for time allocation proposals expands this core value to the science community.

The SMO, run by USRA on behalf of NASA, has transformed several aspects of the hiring process for all positions, including updating the recruitment process to include under-represented candidates, and adding requirements for diversity in hiring committee and candidate pools (e.g., inclusion of at least one woman and one scientist from a historically excluded background). Good faith efforts to increase the diversity of the candidate pool are required if representation is insufficient. These new policies have resulted in a demonstrated increase in the hiring of women and scientists from historically excluded backgrounds.

The mission is committed to continuing to create a more inclusive and equitable community. Several new initiatives (§7.2) in the pipeline will open up new opportunities for early-career scientists, graduate students, and undergraduate interns of diverse backgrounds.

7.2 Nurturing a Diverse and Inclusive Community

SOFIA's impact is influential and far-reaching (Figure 7-2). SOFIA stands out compared to its sibling astrophysical missions because of its human element. Being a crewed airborne mission involves expertise and skills of a wide variety of individuals from multiple professions, including scientists, engineers, pilots, navigators, flight planners, meteorological support, life support, software engineers, mission directors, instrument operators, avionics, and aircraft mechanics [4.1]. Its public outreach activities and targeted initiatives continue to capture the imagination of people around the world

"The SIS was very enthusiastic about the new energy which the new management team, both at NASA and at the SMO, have brought to SOFIA, and in particular in the renewed and strengthened emphasis on science. This manifests itself throughout all elements of the project in ways too numerous to recount, and we applaud all such efforts and note that they build on the efforts of earlier SOFIA leaders who put the observatory on the path to its current successes."

*Michael Werner (JPL) & Sebastian Wolf (Kiel)
Co-chairs of NASA/DLR Project Advisory group*

and provide opportunities for the next generation to pursue their interest in STEM fields. Through the partnership between DLR and NASA, SOFIA significantly impacts the American and German scientific communities as well as the citizens of both countries. Here we describe a selection of notable activities and initiatives:

Public Engagement

During each deployment, the mission receives numerous requests for visits, to talk with staff either one-on-one or at lectures, to take selfies with the flying observatory, and, unsurprisingly, to fly on the aircraft. To respond to these requests, the Project has conducted multiple tours, open houses, and other events, both in

the US and abroad. These outreach events have given the public the opportunity to see the observatory in person and to learn about its engineering marvels and its scientific mission.

While in New Zealand (NZ), during austral summer, the SOFIA mission becomes a local phenomenon. SOFIA has hosted high school and university students, astronomy clubs, Scouts NZ, local civic and social organizations, military cadets, science and technology researchers, and multiple dignitaries and VIPs, including government ministers. SOFIA scientists, mission directors, and flight crews have been invited to speak at multiple venues, such as the Canterbury Astronomical Society. Press requests from radio, TV, and print outlets are numerous. The level of local support and enthusiasm is pervasive and gratifying.

The mission has recently started to engage more in classrooms, ranging from elementary schools to undergraduates [4.2], both locally and abroad. Recent collaboration with the US State Department resulted in three very successful virtual STEM outreach events for high school and university students in Germany when SOFIA was deployed there during the pandemic.

SOFIA's media strategy focuses on measurable objectives to share and amplify NASA's and SOFIA's science vision. SOFIA's scientific discoveries have been featured prominently on www.nasa.gov/sofia and the SOFIA mission blog (blogs.nasa.gov/sofia). Since 2018, 74 stories about SOFIA's science, leadership, and operations have been shared on these NASA platforms. In addition, social media platforms (Twitter, Instagram, and Facebook) are used to engage with the public with on average two posts per week reaching more than 100,000 followers. SOFIA staff also give media

interviews, including recent features on [PBS Nova](#) and [NPR](#). The discovery of water on the sunlit surface of the Moon in October of 2020 was a tremendous media success, reaching 76.7 million members of the public through approximately 3500 media mentions within 24 hours of the announcement.

SOFIA also positively impacts relationships between NASA and other US government agencies as well as foreign governments. To accomplish science missions during deployments, SOFIA enlists and relies on the support of multiple US and foreign organizations [3.2, 3.3]. For example, the US Embassy assists with overflight clearances and coordination within the government of NZ. As part of their diplomatic mission, Embassy personnel are very supportive of NASA and SOFIA, and advocate for our mission as an example of collaboration and goodwill between the two countries. This support and advocacy extends not only to the general public, but across all levels of government as well. The NSF supports our use and access of the USAP facilities in Christchurch. The US Air Force supports our ferry flight stopovers between NZ and California. On the NZ side, SOFIA relies on enthusiastic support from the civil aviation and airport authorities, the national weather service, the Royal New Zealand Air Force, Air New Zealand, the city of Christchurch, and the province of Canterbury, in addition to multiple local service

providers. Similar levels of collaboration with the governments of Germany and French Polynesia led to successful SOFIA deployments and positive impacts on the local communities. [3.2, 3.3]

Teachers and Students

SOFIA has a long and very successful history of providing critical support for the Airborne Astronomy Ambassadors Program (AAA) and its equivalent German program through which teachers receive professional development, training, and support for implementing new STEM curricula for middle school, high school, and, community college classrooms. The AAA program was initially part of the SOFIA Project, but it is now directly funded by NASA SMD. To date, over 200 U.S. teachers have flown on SOFIA and shared their new skills and knowledge with their students. These teachers have reached over 20,000 students since 2011, in 37 states plus the District of Columbia. About 50 German school teachers have participated, and through their initiatives reached about 50,000 young people.

The AAA program partners with school districts chosen based partly on their participation in the National School Lunch Program. Due to the historical context of the United States, these districts also disproportionately serve students of color. Onboard SOFIA teachers interact with scientists, mission crew, and pilots to learn

Inspiring the Next Generation Worldwide

SOFIA mentors and inspires the next generation by providing opportunities at all career levels for a diverse set of professions: teachers, high-school and community college students, undergraduates and graduate students, mission support and engineering.



TEACHERS & STUDENTS

- 250 U.S. and German teachers participated in scientific observing onboard SOFIA
- >50,000 Students reached
- Immersive experience with SOFIA scientists and crew enhances STEM learning and engagement of both teachers and students

SOFIA INTERNS

- 21 Interns since 2018
- New SOFIA internship program will double these opportunities and will target minority serving institutions
- Interns describe their experience as “key turning points in their career”

EARLY CAREER SCIENTISTS & ENGINEERS

- >250 Guest Observers flown incl. Postdocs and graduate students
- >10,000 people reached since 2019 through open houses in US and overseas
- Numerous science outreach events
- New SOFIA Far-IR school

MISSION LEADERS

- SOFIA is a critical stepping stone
- >15 SOFIA team members are now in leadership positions at NASA centers
- Two early career positions in science and operations specifically to obtain mission operations, technical, and management experience



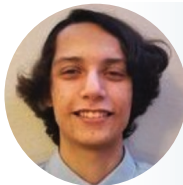
Credit: NASA / SOFIA / Monika Rose

Figure 7-2 SOFIA provides opportunities at all career levels in both science and engineering. The diversity of professions and expertise on SOFIA creates a natural pipeline for building the next generation of mission leaders.



After working as a SOFIA intern, Jose Monzon was inspired to pursue astrophysics. He is now enrolled as a graduate student of astronomy at Yale University.

about SOFIA science and operations. Once they return to their schools, these teachers are equipped to provide their communities with specialized educational opportunities that are designed to measurably enhance STEM learning and engagement of their students. One of the major findings from this recent study was that the students whose teachers were in the AAA program and flew on SOFIA internalized that there are multiple ways of becoming a STEM professional, that STEM is collaborative (rather than solitary), and that STEM requires many different skills. These students also had a marked increased interest in becoming STEM professionals after their teachers participated in the AAA program. The symbiotic relationship between SOFIA and the AAA program also provides opportunities to the SOFIA team members, who are very passionate about outreach.



Jorge Vazquez and other interns talk about how working with SOFIA ignited a passion for astrophysical research that started their scientific careers.

SOFIA Internship Program

Since 2018, SOFIA has worked with 21 interns, both during summer terms and during the school year. These students have a wide variety of backgrounds and interests. Many of them have described their internship experiences as key turning points, inspiring them to become STEM professionals.

A new internship program starting Spring 2022 will formalize SOFIA's previous internship efforts and provide specific funding to serve approximately 15-20 interns per year, including the opportunity to fly and observe on SOFIA. SOFIA will work within the current NASA internship infrastructure to advertise positions and select interns. SOFIA will also partner with the Office of STEM Engagement (OSTEM) at Ames and recruit students from minority-serving institutions, including Historically Black Colleges and Universities, Hispanic Serving Institutions, Tribal Colleges and Universities, and Asian American and Native American and Pacific Islander Serving Institutions [4.2].



Krystal Paul's trajectory completely changed after interning with SOFIA. While not planning to continue after community college, she is now in an electrical engineering program with the goal of working in systems engineering at NASA.

Through this new formalized internship program, SOFIA will provide a cohort-model internship experience to foster networking and community building for the interns themselves, and the interns' mentors will provide scientific and engineering research experiences. The mentors will be offered Bystander Intervention Training that includes an in-depth discussion of micro-aggressions, to ensure that we are creating an open and welcoming environment. We will offer interested students the opportunity to continue their research during the school year, following the guidelines and term limits for NASA interns, and we will track SOFIA interns to continue to support and celebrate their achievements after they complete the program.

In addition to the internship program, the mission is contemplating a unique co-op program, targeting minority-serving institutions, to support mission operations during the Southern Hemisphere deployments. This will allow students to gain critical hands-on skills in mission planning and execution.

Building Mission Leaders

SOFIA has long been an important career stepping stone for science, engineering, and aviation professionals. Because SOFIA is such a versatile platform, the work environment naturally supports cross-functional activities and provides a holistic experience that helps team members increase the diversity of their skillsets and/or advance upwards in their career paths [4.1]. Select examples are below:

- At least 15 people (current or retired) who worked with SOFIA at some point in their careers have become leaders at ARC and AFRC (e.g., deputy center director, director of operations at both centers, engineering branch chiefs).
- The current SOFIA Project Scientist was appointed by ARC and NASA HQ to this major leadership role on a flagship-class NASA mission at an early career stage.
- A four-year "Associate Project Scientist" temporary civil service position has been created and filled for an early-career astronomer or planetary scientist to get hands-on experience on a NASA mission while also allowing for 40% science research time.
- An AFRC (in-kind) technical excellence position in SOFIA operations engineering and management provides the opportunity for an early-career engineer to support and manage many aspects of observatory operations and deployments.
- SMO's multi-level management structure has supported development of employees into leadership positions internally to the manager and associate director level. Former SMO employees have gone on to become directors at other observatories (e.g., Green Bank Observatory).

➤ SOFIA provides unique training in instrumentation for both engineers and scientists, including PIs of instruments, that prepares these people for leadership roles in other NASA missions.

7.3 Project's Perspective on Operations and Efficiency

Project Reorganization

As expected of missions in the extended phase, the SOFIA Project reorganized in 2019 following guidance from NASA HQ to achieve a sustainable operations model at \$80M, below the appropriated \$85.2M annual in-guide budget. The additional funds (\$5.2M) will be used for augmentation of the mission, primarily for new or enhanced instrumentation.

The reorganization minimized complexity and reduced management overhead costs. The Project executed a 10% reduction in workforce in non-science work areas with an acceptance of operating at a higher risk (Figure 7-3). Changes implemented included:

➤ Streamlining aircraft operations by reducing the Operations Division civil servant management structure, the aircraft operations contractor workforce, and the aircraft equipment and maintenance costs.

➤ The Operations Director civil servant position was eliminated, and the SOFIA Operations Division is now managed by the Deputy Project Manager for Operations.

➤ The Observatory Systems Division was merged with operations, reducing additional management overhead. Some civil servant and contractor sustainability engineering tasks were eliminated. With a reduced sustainment engineering staff and limited spares, the mission has a higher mission assurance risk posture.

➤ Project management and administrative tasks were reduced by cut backs of some mission support positions.

➤ The science workforce was augmented (e.g., Associate Project Scientist position). After reorganization, the SMO also found efficiencies that were reinvested into creating additional scientific positions (e.g., postdocs).

With the reorganization in place, the Project leadership identified a set of bold initiatives (e.g., increasing Southern Hemisphere observing time; transitioning EXES to a facility instrument; building a diverse, interdisciplinary SOFIA user community), in addition to implementing all of the FMR recommendations. Some PMOs identified in this proposal were the outcome of these initiatives, which were also enthusiastically endorsed by NASA and SOFIA advisory/user groups. The reorganization also facilitated additional contractor positions to support increase in flights and to enhance science community engagement and user support. Table 7-1 lists key operational and efficiency initiatives, both current and future, to be implemented within the \$80M operating budget, except for the HAWC+ instrument upgrade, which is covered under the additional

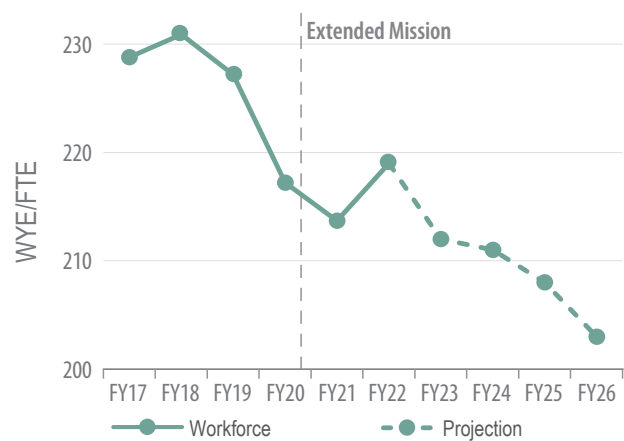


Figure 7-3 Historical and future projections for the SOFIA workforce. Not all the planned staffing reductions could be implemented due to the COVID-19 pandemic and some technical challenges that required Project to preserve skill sets. The full 10% reduction is expected over the next three years

\$5.2M set aside for new instrument development and upgrades. The Project will swiftly reassess if some initiatives (e.g., more Southern Hemisphere deployments) cost more than anticipated. Trades will be identified and discussed with stakeholders before proceeding.

COVID-19 Impacts to SOFIA Operations

The COVID-19 pandemic impacted SOFIA more than any other NASA astrophysics mission, because unlike space missions, SOFIA cannot be operated remotely. SOFIA suspended operations, effective March 19, 2020 and resumed August 17, 2020, starting with a limited number of flights. SOFIA lost over 73 flight opportunities (~600 research hours). Some aspects related to this lost observing time are:

➤ 45 science flights lost from March to August 2020.
 ➤ Additional loss of 28 science flights due to the cancellation of the 2020 Summer Southern Hemisphere deployment, which also led to the loss of substantial observing time for the community Legacy programs, German guaranteed-time programs, Priority-1 and Priority-2 U.S. GO programs.

➤ In February 2021 when the COVID-19 situation in California was at its worst, SOFIA moved operations to Germany where it was safer to conduct operations.

➤ 2021 Summer Southern Deployment moved to French Polynesia due to the continued travel restrictions imposed by the New Zealand government. SOFIA was forced to return home early due to significant rise in COVID-19 cases, accomplishing only 13 of 32 planned science flights.

➤ COVID-19 protocols restricted flight duration to 8 hours (rather than the nominal 10) to limit staff fatigue due to strict PPE requirements (e.g., N95 masks). This rule was lifted on June 25, 2021 with easing in COVID restrictions following CDC guidance. SOFIA has returned to 10-hour flights.

Table 7-1 Achievements and status of Project's current & planned future operations and efficiency initiatives.

Observatory Operations & Efficiency (aircraft/mission)	Metric/Impact	Status
Move to single annual aircraft/observatory maintenance period to increased observing time	§5.1, Figure 5-1 & 5-2	Sept 2021 ✓
Build the operational capacity to plan for a weekly contingency flight	§5.1, Figure 5-1 & 3-3; Reliability	July 2021 ✓
Increase the total number of flights in Southern Hemisphere to 50 annually	Figure 5-1 & 5-2	In progress ✨
Establishing alternate deployment sites (French Polynesia & Chile done)	§6.7 & 5.1	Dec 2021 ✓
5 engines purchased to extend mission lifetime	Reliability	Oct 2021 ✓
Cross Training of mission operations to reduce staffing onboard SOFIA	Table 4-1 Efficiency & Reliability	In progress ✨
Automation of flight planning and mission operations tasks	§5.3.3	July 2021 ✓
Implementing high speed internet on SOFIA (supports Tech. PMO#1)	§6.8.1	Starts 2024
Science Operations & Efficiency	Metric/Impact	Status
Increased fraction of Legacy Programs to 30%	§5.4	Achieved ✓
New SOFIA Archival Call	§3.2.1	July 2020 ✓
Transition to IRSA Archive; Four Archive updates released over 1.5 yrs	Figure 3-4	March 2020 ✓ Oct 2021 ✓
Incorporation of water vapor in flight planning & scheduling observations	§5.1 & 5.3.1	Started
Increasing grant funding threshold for GOs to \$75K	§3.3 & 7.4.1 User Support & Faster Publications	Oct 2021 ✓
Automation of Science Operations functions	§5.3; Efficiency & Higher Quality	Complete ✓
Data processing in 15 working days for all facility instruments	§4	Achieved ✓
Programmatic	Metric/Impact	Status
SOFIA Instrument Roadmap developed HAWC+ upgrade formulation effort funded (Step 1)	Figure 5-4	In Progress ✨
EXES transition from PI to facility science instrument	§4 & 3.1.1; Efficiency, Science Return & User Support	Oct 2021 ✓
Embracing Inclusion: (1) dual anonymous reviews; (2) SOFIA far-IR school for early career scientists; (3) SOFIA internship program; (4) SOFIA postdocs	§7.1 & 7.2; Figure 7-2	(1) & (4) Complete ✓; (2) & (3) in progress ✨

✓ = Implemented ✨ = COVID-19 impact

The overall Cycle 8 science observations were severely impacted by COVID-19. The mission replanned the entire set of observations to minimize impact and maximize completion of high-priority science programs.

Budgetary Decisions

The Project utilizes NASA's annual PPBE process to assess, evaluate, and update the plan of budget execution. In preparation for the annual PPBE, the Project reaches out to the leads of all key functional areas (shown in Figure 7-4) to solicit the funding needed in their areas to execute the planned mission and proposals on new investments. Any new investments must be justified by efficiency improvements, increased reliability, increasing scientific productivity, or better user community support. If resources become insufficient to meet all the objectives in a given year, the leadership team, in concert with SOFIA's stakeholders, evaluates and selects the course of action that promises the best overall productivity.

7.4 Budget

7.4.1 In-guide Budget

The in-guide budget for SOFIA is \$85.2M. Historically, like Hubble, SOFIA's budget is appropriated as a line item (\$85.2M) by the US Congress. This requires the Project to plan and spend the entirety of these funds following the direction and guidance from NASA HQ.

The SOFIA budget consists of both fixed and variable costs. The majority of the fixed cost supports a combined workforce of ~214 FTEs and WYEs (Civil Servants and Contractors, respectively). When the observatory is grounded for technical reasons, workforce salaries are still covered. The majority of variable costs relate to fuel. Fuel prices fluctuate and can vary at different deployment sites. If planned flights do not take place, the funds held for the fuel of those flights are available for redistribution; that is, these resources can be strategically reinvested to enhance scientific return and user support. The funding for GOs can also

vary from year to year, depending on how many GOs are from U.S. versus foreign institutions. If additional GO funds do become available, they are invested in SOFIA archival calls.

The historical and current distributions of funds, including the workforce breakdown, are shown in Figure 7-4. Typical space observatories have costs that are incurred early in their development and launch. These costs are not reflected in their current operating budgets. In contrast, a substantial fraction of SOFIA's current operating budget (e.g., fuel, safety, hangar infrastructure, instrument development) that may be comparable to a space mission in its early phase are essentially spread out over the lifetime of the mission. Some of these costs are highlighted in Figure 7-4 in blue. The reorganization (§7.3) shifted costs from operations to science. Reductions in development (e.g., observatory systems) and in project management shifted funds to science operations, developing the data archive, and improving user support. During the prime mission, when multiple instruments were in development and being commissioned, the costs for science instrument development and support staff were much higher. Since FY17, the workforce has been reduced from ~229 to ~214 due to continued efforts by the project management to

optimize science productivity, minimize complexity, and reduce management overhead.

Starting in FY21, the operating cost of SOFIA was reduced to \$80M. This includes aircraft operations, mission operations, science operations, GO funding, fuel, and public engagement. The remaining funds (~\$5M) are primarily dedicated to developing new instruments and upgrading to existing science instruments (§5.6). All the current and new proposed initiatives are covered by the in-guide budget. Because SOFIA is an airborne mission, day-to-day operations are dynamic and can be heavily impacted by external factors. Thus, as the mission progresses through a given fiscal year, deviations from the planned budget are expected. Because of this dynamic nature of SOFIA's operating budget, there is some flexibility within the \$80M operating cost to strategically reinvest funds.

In FY21, unused fuel funds were redistributed to increase the funding available (\$1.8M) for the new SOFIA standalone archival Call for Proposals and to improve the data archive at IRSA (~\$0.5M). The Project will continue to invest at least \$2M annually on archival calls without compromising existing GO funding for the awarded observing programs. The Project recently established a minimum threshold for GO funding of

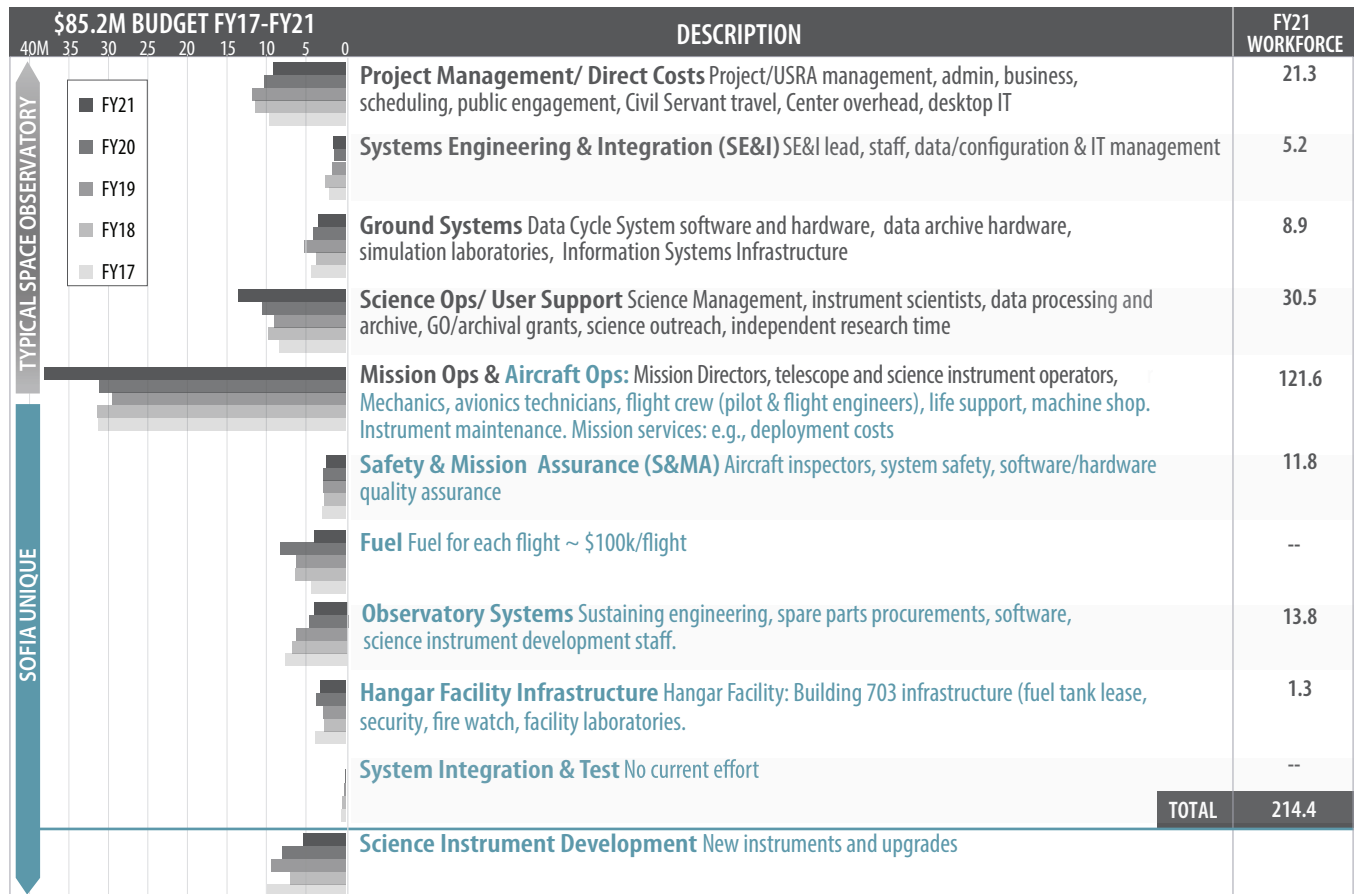


Figure 7-4 (Left) SOFIA budget trends since FY17. (Right) Workforce breakdown for FY21. The science instrument development is shown separately from the \$80M operating budget. SOFIA unique costs in blue. A typical space observatory operating budget will not include comparable costs, which are incurred during their development and launch phases.

\$75,000. This allows GOs with smaller programs (i.e., awarded 30 minutes to 4 hours of observing time) to be able to support a postdoc or graduate student to analyze SOFIA observations and publish the results. The project will continue to evaluate and reallocate unused fuel funding to increase scientific return and maintain the observatory's reliability.

The tables and figures within this section follow the standard NASA Work Breakdown Structure (WBS) that is used by all missions to plan, execute, and track the budget. The breakdown presented in [Figure 7-4](#) uses the highly detailed NASA WBS. Appendix B (Budget Spreadsheet) provides a different breakdown following the instructions in the Call for Proposal. This required the Project to make certain assumptions to fit in the requested format. Additional notes are included in the budget spreadsheet to indicate the functional areas included under a requested line item. SOFIA does not require *Space Communication Services*, and *Science Data Analysis* is performed by the Guest Observers or Legacy teams. *Mission Services* includes multiple WBS items such as *Systems Engineering & Integration*, *Safety & Mission Assurance*, *Observatory Systems*, and *Fuel*. *Other Mission Operations* include *Mission and Aircraft Operations* and *Ground Systems*.

Current In-kind Support

USRA (\$200K) in-kind contributions include (1) hiring additional postdocs, (2) travel funding for SOFIA scientists for building collaborations, (3) funding SOFIA Staff Science Symposia to discuss their individual research and foster scientific collaboration and team building, and (4) funding a new Diversity and Inclusion Internship initiative with three universities to host six students and three mentors from under-represented groups.

AFRC in-kind contributions are 1 FTE for the Project Chief Engineer, who represents the engineering technical authority and 1 FTE for the Project Operations Manager, who represents the airworthiness technical authority

DLR in-kind contributions include management personnel at DLR (5 FTEs) and DSI/University Stuttgart (15.4 FTEs) and supporting the GREAT instrument team (8-10 FTEs)



8. PROJECT DATA MANAGEMENT PLAN

SOFIA's information management aligns with the SMD Scientific Information policy by retaining permanent archives of scientific data; complying with a reasonable exclusive use period; providing free, public access to SOFIA data at IRSA; and publicly releasing its pipeline

software delivery to IPAC for distribution to the community. The distribution of data via IRSA is consistent with the SMD policies of providing free, public access to SOFIA data in standard machine-readable formats and the archive assures the preservation of SOFIA's scientific information..

SOFIA provides the astronomical community mid- to far-IR data that are easily accessible and in a standard format. SOFIA instruments utilize a variety of different technologies, observational techniques, and has multiple data types. SOFIA's pipelines handle all of this complexity and distill the raw data into science-ready data products, including (but not limited to) cleaned and flux-calibrated continuum images and line maps, wavelength/flux-calibrated and telluric-line-corrected spectra, and calibrated polarimetric maps. These data products are archived within 15 working days from the flight date (GREAT, a German PI-class instrument, has a 60-day requirement). To make SOFIA data available to the community more quickly, SOFIA has decreased its exclusive use period from 12 to 6 months for standard observations (users have an option to waive the exclusive use period for their data). There is a special exclusive use period of 12 months for a small number of thesis-enabling projects, to allow extra time for analysis and publication during early career development. Data obtained as part of Legacy or Director's Discretionary Time data observations have no exclusive use period.

To allow users to better understand SOFIA data reduction, and to reprocess data to meet their individual needs, SOFIA is publicly releasing its pipeline software (with detailed user manuals and tutorials) under an open source license. Included in this effort is the translation of all pipeline software to Python, an open source programming language embraced by the astronomy community. As of January 2022, all FSI instruments have had their pipelines released, save EXES which just became a FSI in the winter of 2021. The pipeline for EXES is expected to go public sometime in late 2022. In keeping with SMD policy, this software is provided free of cost to the scientific community.

SOFIA has worked with IRSA to implement several enhancements designed to provide the community with easy access to SOFIA data and related publications. Among these are visualization of all SOFIA data types, enhanced search capabilities, the display of quality assurance comments and publication information, and the ability to preview images of all high-level data products, allowing an astronomer to peruse the SOFIA data without having to download them first.



SOFIA Magnetic Field Streamlines in the Keyhole Nebula

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APPENDICES

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Appendix B. Standard Budget Sheets

This page was a placeholder for budget spreadsheets in preparation for the 2022 Astrophysics Senior Review.

Appendix C. Acronym List

S	Section	FPI	Focal Plane Imager
	SMD Science Plan Strategy 1: Exploration and Scientific Discovery	FPR	Flight Preparedness Report
	SMD Science Plan Strategy 2: Innovation	FSI	Facility Science Instrument
	SMD Science Plan Strategy 3: Interconnectivity & Partnerships	FTE	Full-Time Equivalent
	SMD Science Plan Strategy 4: Inspiration	FY	Fiscal Year
AAA	Airborne Astronomy Ambassadors	GO	Guest Observer
AAS	American Astronomical Society	GREAT	German REceiver for Astronomy at Terahertz Frequencies
AFRC	Armstrong Flight Research Center	GSFC	Goddard Space Flight Center
AGU	American Geophysical Union	GTO	Guaranteed Time Observation
ALMA	Atacama Large Millimeter/Submillimeter Array	GUSTO	Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory
AOG	Aircraft on Ground (Boeing)	HAWC+	High-resolution Airborne Wideband Camera
APAC	Astrophysics Advisory Committee	HIRMES	High-Resolution Mid-Infrared Spectrometer
APRA	Astrophysics Research & Analysis	HQ	Headquarters
ARC	Ames Research Center	IPAC	Infrared Processing & Analysis Center
Astro2020	Decadal Survey on Astronomy and Astrophysics 2020	IRSA	Infrared Science Archive
BLASTPol	Balloon-Borne Large-Aperture Submillimeter Telescope -Polimeter	IR	Infrared
CDDS	Cavity Door Drive System	IRTF	Infrared Telescope Facility
CECS	Cavity Environment Control Systems	ISM	Interstellar Medium
CGM	Circumgalactic Medium	ISO	Infrared Space Observatory
Co-I	Co-Investigator	JPL	Jet Propulsion Laboratory
CTIO	Cerro Tololo Inter-American Observatory	JWST	James Webb Space Telescope
DI	Downing Item	KID	Kinetic Inductance Detector
DDT	Director's Discretionary Time	LIGO	Laser Interferometer Gravitational-Wave Observatory
DLR	Deutsches Zentrums für Luft und Raumfahrt (German Aerospace Center)	LMC	Large Magellanic Cloud
DSI	Deutsches SOFIA Institut (German SOFIA Institute)	LRU	Line Replaceable Unit
EOCS	External Observatory Connections System	LSST	Legacy Survey of Space and Time
EXES	Echelon-Cross-Echelle Spectrograph	MCCS	Mission Controls and Communication Systems
FAA	Federal Aviation Authority	MHD	Magnetohydrodynamics
Far-IR	Far Infrared	Mid-IR	Mid-Infrared
FIFI-LS	Far Infrared Field-Imaging Line Spectrometer	MIRI	Mid-Infrared Instrument
FMR	Flagship Mission Review	MOPS	Mission Operations Science
FOC	Full Operational Capability	NASA	National Aeronautics and Space Agency
FORCAST	Faint Object InfraRed CAmera for the SOFIA Telescope	NIST	National Institute of Standards and Technology
		NPR	National Public Radio
		NSF	National Science Foundation
		NZ	New Zealand

ODC	Other Direct Costs
OSTEM	Office of STEM Engagement
PBS	Public Broadcasting Service
PDR	Photodissociation Region
PI	Principal Investigator
PIS	Platform Interface Subsystem
PMO	Prioritized Mission Objective
PPBE	Planning, Programming, Budgeting, and Execution
PPE	Personal Protective Equipment
PSI	Principal Investigator Science Instruments
PWV	Precipitable Water Vapor
SARP	SOFIA Archival Research Program
SAT	Strategic Astrophysics Technology
SED	Spectral Energy Distribution
SFR	Star-Formation Rate
SIS	SOFIA International Summit
SMD	Science Mission Directorate
SMO	Science Mission Operations
S/N	Signal to Noise
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOMER	SOFIA Operations and Maintenance Efficiency Review
STEM	Science, Technology, Engineering, and Mathematics
STICS	Science and Technology International Council for SOFIA
STScI	Space Telescope Science Institute
TAAS	Telescope Assembly Alignment Simulator
TAC	Time Allocation Committee
TES	Transition-Edge Sensors
TEXES	Texas Echelon-Cross-Echelle Spectrograph
USRA	Universities Space Research Association
USAP	US Antarctic Program
VIPER	Volatiles Investigating Polar Exploration Rover
WBS	Work Breakdown Structure
WYE	Work-Year Equivalent

Appendix D. Link to Online Bibliography

D.1 Refereed Publications:

<https://www.sofia.usra.edu/science/publications/sofia-publications>