

SOFIA Science



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Composite infrared image of the center of our Milky Way galaxy. Subset of the full image on page 9, highlighting the Arched Filaments (left) and Sagittarius A (right). (NASA/SOFIA/JPL-Caltech/ESA/Herschel)

SOFIA Observers Resources

SOFIA offers the following tools and documentation to facilitate the proposal process. These resources are available at: www.sofia.usra.edu/science/proposing-observing

Core Documentation

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

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

Proposal Submission Tools

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

submitting proposals for SOFIA, with specific instructions for each instrument.

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

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

Public Archival Data

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

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

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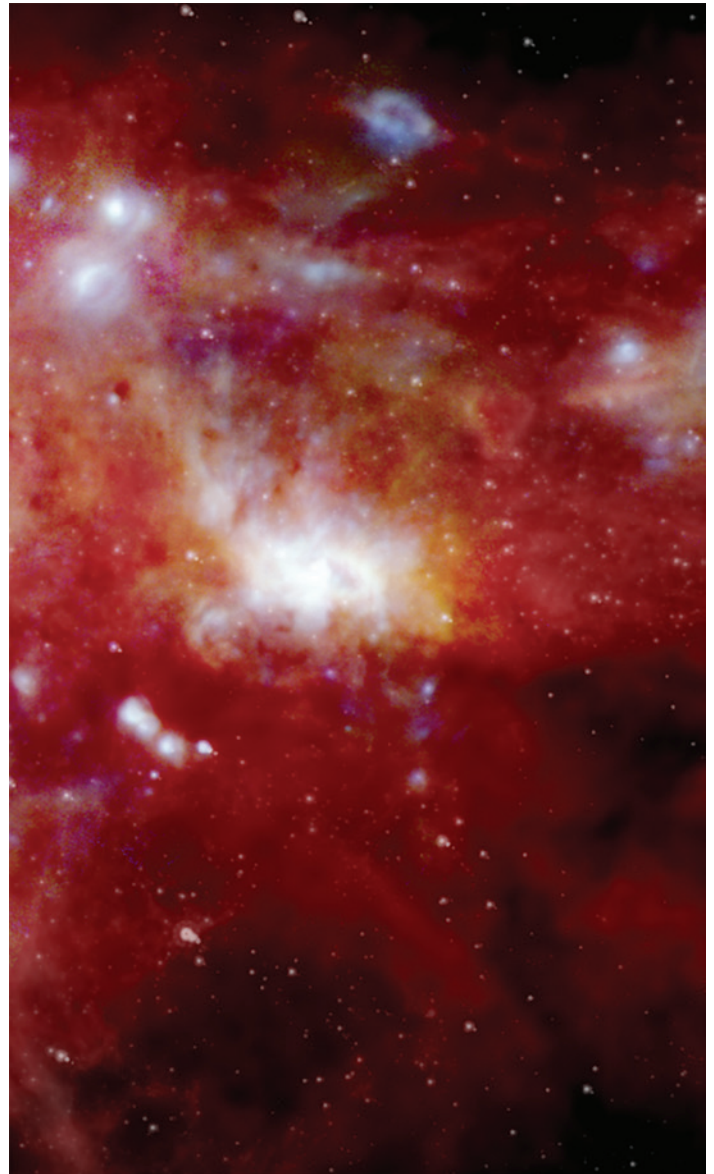


Signatures of Star Formation in the Galactic Center

SOFIA's first completed [legacy program](#) provides researchers with a vastly improved view of warm dust in the center of the Galaxy, revealing signatures of star formation in exquisite detail.

The inner ~200 pc of the Milky Way contains some of the most extreme conditions for star formation in our Galaxy — high molecular gas densities, high gas and dust temperatures, significant turbulence, and a strong gravitational potential well. It's thought that the environment in the Galactic center is somewhat similar to what is found in actively star forming galaxies, yet its relative proximity enables detailed study of physical processes at a level that is inaccessible in more distant galaxies. However, the global star formation rate of the Galactic center is deficient by more than an order of magnitude compared to theoretical expectations based on its molecular gas reservoir. This inefficiency in transforming dense gas into stars is a significant quandary in our understanding of the region and has potentially broad implications for observational star formation tracers that are used to study other galaxies.

Several common star formation diagnostics at optical and UV wavelengths cannot be used to study the Galactic center because of heavy extinction caused by gas and dust along our line of sight. Instead, studies of star formation have largely relied on infrared observations from missions like Spitzer and Herschel which were able to pierce through the line of sight dust. Warm dust emission at ~24 μm is a



Composite infrared image of the center of our Milky Way galaxy. Subset of the full image on page 9 centered on the Sgr A complex. (NASA/SOFIA/JPL-Caltech/ESA/Herschel)

particularly useful probe of recent star formation activity; however, the brightest regions within the inner ~200 pc

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About this Spotlight

Paper: SOFIA/FORCAST Galactic Center Legacy Survey: Overview

Authors: M. J. Hankins, R. M. Lau, J. T. Radomski, A. S. Cotera, M. R. Morris, E. A. C. Mills, D. L. Walker, A. T. Barnes, J. P. Simpson, T. L. Herter, S. N. Longmore, J. Bally, M. M. Kasliwal, N. B. Sabha, M. Garcia-Marin

Reference: 2020, *ApJ*, in press.

Science Spotlight

Elena Redaelli, *Max Planck Institute for Extraterrestrial Physics*
Joan Schmelz, *Universities Space Research Association*



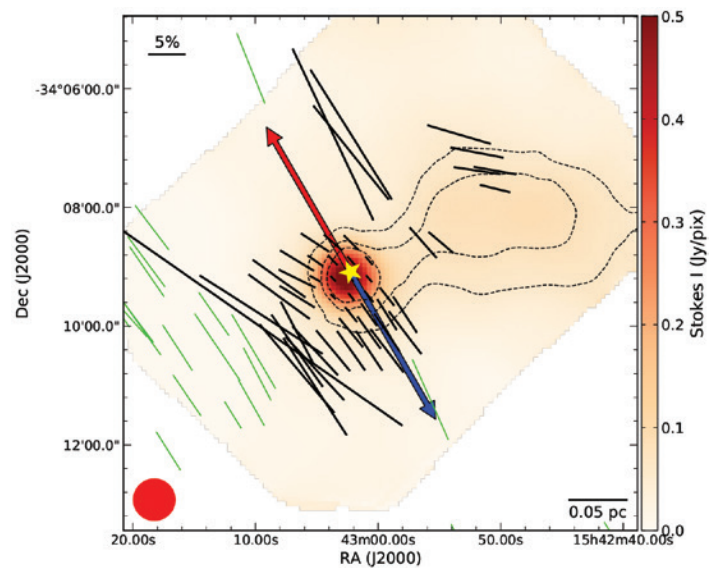
A Magnetic Hourglass Detection for a Low-Mass Protostar

Magnetic fields (B) are ubiquitous in interstellar space, and their role in the star-formation process is of fundamental importance. However, how they interplay with other important forces — such as gravity and turbulence — are topics currently under great debate. At the scales of dense cores (fractions of parsec), the theory of magnetically-driven collapse in a uniform field predicts first the formation of a flattened structure (a pseudodisc), since the matter can only flow along the field lines; later, the gravitational pull grows strong enough to pinch the field lines, giving rise to a characteristic hourglass shape. However, such a feature has been observed only rarely, especially in low-mass objects, for which there are only two clear detections reported in the literature.

Magnetic fields are difficult to detect, but the High-resolution Airborne Wideband Camera Plus (HAWC+) on SOFIA observes polarized dust emission at far-infrared wavelengths that are not accessible from the ground. The dust particles are predicted to align with the local magnetic field, giving rise to thermal radiation polarized perpendicularly with respect to B .

As part of its southern deployment to New Zealand in 2018, SOFIA sought to study the initial stages of low-mass star formation in a highly magnetized environment. HAWC+ targeted the low-mass protostellar core IRAS 15398-3359, which hosts a protostar younger than 10^4 yr. It is embedded in the Lupus I molecular cloud, the least evolved component of the Lupus complex.

Previous optical polarimetry of this cloud, which traces the low-density cloud-scale magnetic field, revealed a uniform strength of $B \approx 100 \mu\text{m}$ and a field structure



The Stokes I map of IRAS 15398 obtained with HAWC+, with overlaying polarization vectors from SOFIA (black) and from optical (green) polarimetry. The protostar position is shown with a star, and arrows show the outflow direction. (Redaelli et al., 2019.)

aligned perpendicularly to the main axis of the cloud. We obtained new polarimetric HAWC+ data at $214 \mu\text{m}$.

The optical and far-infrared polarization vectors both trace a common direction indicating that the core preserved the magnetic field morphology inherited by the parental cloud while it was evolving and contracting. The far-infrared data close to the central protostar reveal a uniform field that is roughly aligned with the outflow direction, as predicted by the theory of magnetically-driven collapse. However, on the south-east side of the core, the field lines pinch inward, unveiling a (partial) hourglass shape. This is not detected on the other side, possibly due to limited sensitivity. If confirmed by further, deeper observations, this would represent the first hourglass shape detected by SOFIA in the low-mass regime.

A statistical technique known as angular dispersion

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About this Spotlight

Paper: Magnetic Properties of the Protostellar Core IRAS 15398-3359

Authors: E. Redaelli, F. O. Alves, F. P. Santos, P. Caselli

Reference: 2019 A&A, 631, A154.



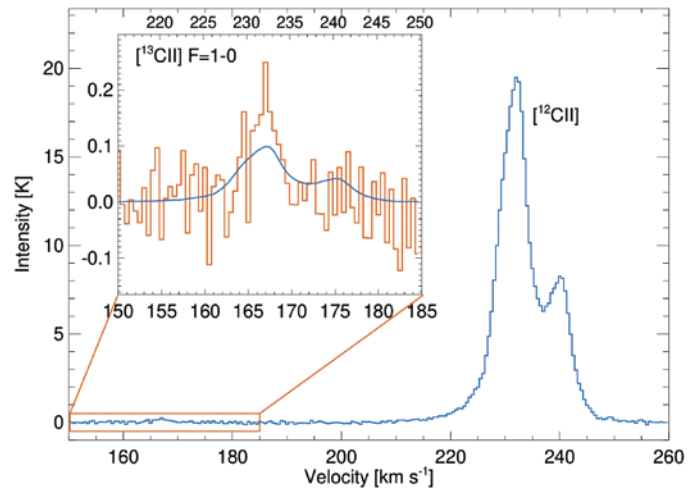
SOFIA Reveals the Complex Nature of a ‘Simple’ Star Formation Tracer

The cosmic cycle of star formation is an essential part of the evolution of the universe. The far-infrared fine structure line from singly ionized carbon (C^+) at $158\ \mu\text{m}$ (transition $^3P_{3/2} - ^3P_{2/1}$; hereafter [CII]) is one of the important tracers of star-forming activity in near and far galaxies. The ultraviolet radiation from massive stars creates warm layers on the surface of the surrounding molecular clouds, where the energy balance is maintained by cooling the gas through emission lines like [CII] $158\ \mu\text{m}$.

Observations of [CII] have become more important recently because the cosmological redshift moves the line from distant galaxies into the band detectable by the Atacama Large Millimeter/submillimeter Array (ALMA). Many scientists use the strength of this spectral line as a direct indicator of the star formation rate in those galaxies that appear only as a point source. Observations in the nearby universe are helping to determine if this simple assumption is valid.

Recent SOFIA observations have revealed more and more cases of optically thick [CII] emission from Galactic star-forming regions. Now we have the first results from the Large Magellanic Cloud, one of the best-studied star formation laboratories outside our Galaxy. These results indicate that the intensity of this line may be underestimated by a factor of approximately two.

The only observational way to estimate the optical depth of the [CII] line is to compare it with the hyperfine emission from its isotope — $^{13}C^+$. Because the wavelength of the $[^{13}CII]$ emission is less than $0.03\ \mu\text{m}$ away from



Spectrum of the $[^{12}CII]$ and $[^{13}CII]$ emission at the position where the integrated intensity of [CII] is strongest in the star-forming region N159W in the Large Magellanic Cloud. The blue line overlaid on the $[^{13}CII]$ spectrum is the scaled $[^{12}CII]$ emission that would be expected if the $[^{12}CII]$ emission were optically thin. The observed intensity of $[^{13}CII]$ is stronger than the scaled $[^{12}CII]$, indicating that the $[^{12}CII]$ emission is optically thick. (Okada et al., 2019.)

the $[^{12}CII]$ line, very high spectral resolution is required to separate these features. The heterodyne instrument upGREAT (German Receiver for Astronomy at Terahertz Frequencies) onboard SOFIA provides this opportunity.

SOFIA detected $[^{13}CII]$ in three active star forming regions in the Large Magellanic Cloud for the first time. Results indicate that the intensity of the $[^{12}CII]$ emission is lower by a factor of about two compared to that expected from the $[^{13}CII]$ emission. The most likely explanation for this disagreement is that the $[^{12}CII]$ emission is optically thick.

The alternative explanation — that the isotopic ratio $^{12}C/^{13}C$ is lower than reported in the literature — can be excluded for two reasons. The first is that the intensity

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About this Spotlight

Paper: First Detection of $[^{13}CII]$ in the Large Magellanic Cloud

Authors: Y. Okada, R. Higgins, V. Ossenkopf-Okada, C. Guevara, J. Stutzki, M. Mertens

Reference: 2019, A&A, 631L, 120.

Science Spotlight

Cristian Guevara, *University of Cologne*

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The Optical Depth of [CII]: the Implications for Galaxies both Near and Far

Photodissociation Regions (PDRs) are zones of the interstellar medium in which Far-UV photons dominate the thermal balance, chemistry, structure, as well as the distribution of the gas and dust. The incident FUV field photodissociates molecules, photoionizes atoms and molecules, and heats the gas and dust.

The [CII] 158 μm fine structure line in the far IR is one of the brightest emission lines in PDRs and provides an important cooling mechanism for the atomic and molecular gas. The [CII] line is also used as a vital star-formation tracer for both nearby and high redshift galaxies, but these studies assume that the line is optically thin. If this ubiquitous star-formation tracer is to provide physically meaningful astronomical information, it is essential to know whether the line emission is optically thin or thick.

Interest in the optical depth of [CII] has been present since the first observations of [CII] in the early 1980s. Traditionally, [CII] has been assumed to be optically thin, with systematic measurements of a few cases done only in the last few years. This key analysis required the high sensitivity and spectral resolution of the SOFIA upGREAT instrument.

SOFIA observed simultaneously [^{12}CII] and its isotope [^{13}CII]. The [^{13}CII] line is split into three hyperfine satellites due to the extra neutron, located at 11, -63 and, 65 km/s from the main [^{12}CII] line. The main objectives of this work were to determine the [^{12}CII] optical depth, study the effects that could result from a non-optically thin line, and determine the physical parameters associated with the ionized carbon.

About this Spotlight

Paper: [CII] 158 μm Self-absorption and Optical Depth Effects

Authors: C. Guevara, J. Stutzki, V. Ossenkopf-Okada, R. Simon, J. P. Pérez-Beaupuits, H. Beuther, S. Bihl, R. Higgins, U. Graf, R. Güsten

Reference: 2020, A&A 636, A16.



Composite image of M17 SW. SOFIA detected the blue areas (20 μm), revealing gas as it's heated by massive stars located at the center and the green areas (37 μm) that trace dust as it's warmed both by massive stars and nearby newborn stars. The red areas near the edge represent cold dust that was detected by the Herschel Space Telescope (70 μm), while the white star field was detected by the Spitzer Space Telescope (3.6 μm). The space telescopes could not observe the blue and green regions in such detail because the detectors were saturated. (NASA/SOFIA/De Buizer/Radomski/Lim; NASA/JPL-Caltech; ESA/Herschel)

We observed multiple positions in four different PDRs with a wide range of physical conditions: M43, Horsehead, Monoceros R2, and M17 SW. The results indicate that the [^{12}CII] emission is optically thick, with optical depths ranging between two and seven. In addition, positions in both Monoceros R2 and M17 SW are heavily self-absorbed, with spectral dips that mimic velocity components. Hence, comparisons of velocity profiles without accounting for the optical depth should be treated with caution.

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Science Spotlight

Kathleen Kraemer, *Boston College*
Gregory Sloan, *Cornell University*



The Chemical Enrichment of the Universe

Infrared spectra from SOFIA have uncovered a fundamental difference between the dust produced by two types of carbon-rich variable stars. New FORCAST spectra reveal a close relation to the pulsations racking these evolved stars, as revealed by their variability type as well as the dust and molecules they are producing. The Mira variables, with their strong pulsations, are producing significant quantities of amorphous carbon dust. The semi-regular variables, on the other hand, show little dust, and what dust they have is primarily silicon carbide (SiC).

A fundamental issue in stellar astrophysics is the role of low- and intermediate-mass stars in the chemical enrichment of the Universe. Dust grains can condense in the cool atmospheres of these stars, and radiation pressure on the grains drives mass-loss, with the gas dragged along by the dust. Through this process, stars that started out with about 1–8 solar masses expel the bulk of their material while on the asymptotic giant branch, ultimately ending up as small white dwarfs.

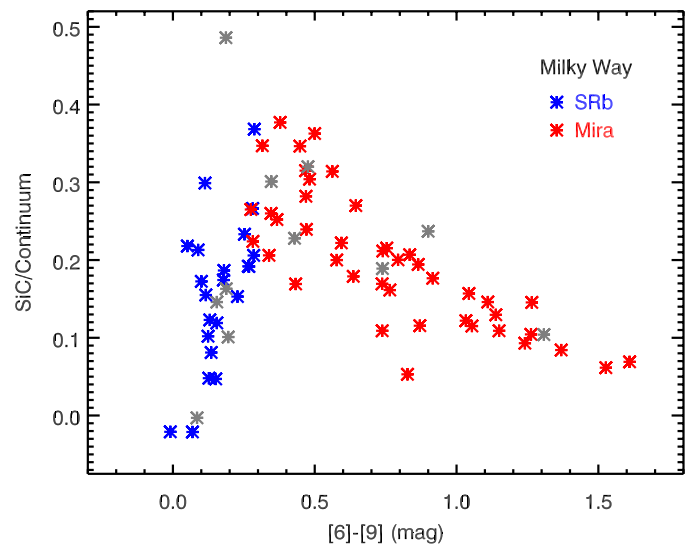
Studies of the Magellanic Clouds suggest that carbon stars may be the dominant source of dust contributed by stars to the interstellar medium. Those asymptotic giant branch stars that dredge enough freshly fused carbon from their interiors to their surfaces become carbon stars. With more carbon than oxygen in their atmospheres, carbon-rich material dominates their chemistry in both the gas phase and in condensing dust. They will quickly embed themselves in optically thick shells of amorphous carbon dust instead of the silicates seen in oxygen-rich stars.

About this Spotlight

Paper: *Stellar Pulsation and the Production of Dust and Molecules in Galactic Carbon Stars*

Authors: K. E. Kraemer, G. C. Sloan, L. D. Keller, I. McDonald, A. A. Zijlstra, M. A. T. Groenewegen

Reference: 2019, *ApJ*, 887, 1.



[6]-[9] vs. SiC strength for carbon stars in the Milky Way. The [6]-[9] color is constructed from small, feature-free wavelength ranges of the spectra at 6 and 9 μm and traces the amorphous carbon content, with redder colors (higher x-axis values) indicating more amorphous carbon. Gray asterisks are Galactic carbon stars that are neither Miras nor SRb variables. (Kraemer et al., 2019.)

Recent spectroscopic studies of carbon stars concentrated on the metal-poor Magellanic Clouds using Spitzer's Infrared Spectrograph. Galactic studies have been hampered by limited samples (as with the Infrared Space Observatory, or ISO, in the 1990s). Spectral surveys could overcome this problem, but the Infrared Astronomical Satellite (IRAS) which flew in the 1980s, had limited wavelength range and low spectral resolution. To address these problems with the Galactic sample, we obtained 5–14 μm spectra with SOFIA's FORCAST of 33 Galactic carbon stars, focusing on the underrepresented variables: semi-regulars and the longest-period Miras.

The new spectra, when combined with the samples from ISO and Spitzer, expose a tight relationship between molecules and dust these stars are generating and their

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Science Spotlight

Kassandra Bell, *Universities Space Research Association*
Arielle Moullet, *Universities Space Research Association*
Joan Schmelz, *Universities Space Research Association*

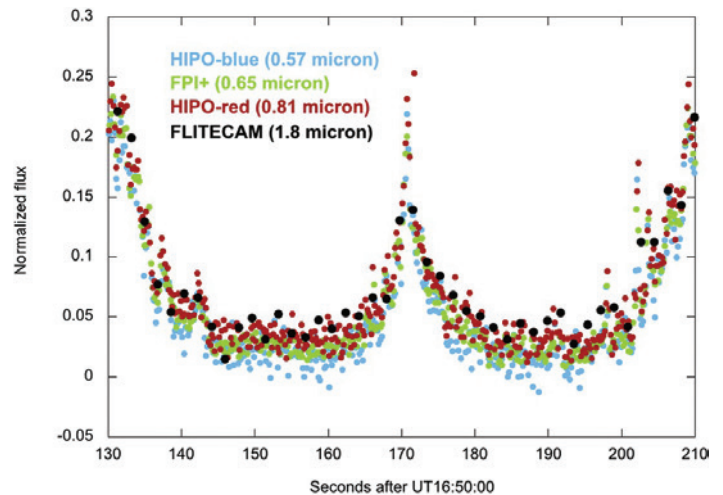


Occultation Confirms Haze in Pluto's Atmosphere

SOFIA observed the occultation by Pluto of a bright star on 29 June 2015, enabling scientists to measure pressure, density, and temperature profiles of the atmosphere of the dwarf planet. Pre-event astrometry allowed the SOFIA team to position the aircraft deep within the central flash zone, just 22 km from the center of the occultation path.

During the occultation, Pluto's shadow traveled at 53,000 mph across the Pacific Ocean. SOFIA flew from its Southern Hemisphere base in New Zealand to observe the occultation event for 120 seconds. It was the only observatory able to position itself in the predicted center of the shadow's path, and therefore able to observe a strong, distinct brightening near the middle of the occultation, called the central flash. This allowed scientists to probe Pluto's atmosphere at low altitudes.

About two hours before the occultation, scientists at MIT contacted the SOFIA in-flight team with the news that the center of the shadow would cross more than 200 miles north of the position on which the airborne observatory's flight plan had been based. After recalculating and filing a revised flight plan, SOFIA's flight crew and science team had to wait an anxious 20 minutes before receiving permission from air traffic control to alter the



flight path accordingly. Observations were taken simultaneously with the First Light Test Camera (FLITECAM), an infrared camera with grism spectroscopy, the High-Speed Imaging Photometer for Occultations (HIPO), an extremely fast and accurate electronic multi-colored imager, and the Focal Plane Imager Plus (FPI+), a fast frame-rate imaging photometer. Together these instruments provided a multi-wavelength view over four photometric bands, from 0.57 to 1.8 μm . These instruments and their ability to be co-mounted on the telescope were designed with this precise observation in mind. Only this sort of simultaneous multi-colored observation can detect the differences in the occultation signatures of clear and hazy atmospheres.

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In order to compare atmospheric characteristics with information retrieved from earlier occultations, the light-

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About this Spotlight

Paper: Haze in Pluto's atmosphere: Results from SOFIA and Ground-based Observations of the 2015 June 29 Pluto Occultation

Authors: M. J. Person, A. S. Bosh, C. A. Zuluaga, A. A. Sickafoose, S. E. Levine, J. M. Pasachoff, B. A. Babcock, E. W. Dunham, I. S. McLean, J. Wolf, F. Abe, E. E. Becklin, T. A. Bida, L. P. Bright, T. Brothers, G. Christie, R. F. Durst, A. C. Gilmore, R. T. Hamilton, H. C. Harris, C. Johnson, P. M. Kilmartin, M. Kosiarek, K. Leppik, S. E. Logsdon, R. Lucas, S. Mathers, C. J. K. Morley, P. Nelson, H. Ngan, E. Pfüller, T. Natusch, S. Sallum, M. L. Savage, C. H. Seeger, H. C. Siu, C. Stockdale, D. Suzuki, T. Thanathibodee, T. Tillemann, P. J. Tristram, W. D. Vacca, J. Van Cleve, C. Varughese, L. W. Weisenbach, E. Widen, M. Wiedemann

Reference: 2020, *Icarus*, in press.

Signatures of Star Formation in the Galactic Center

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are badly saturated in the Spitzer/MIPS 24 μm data. This saturation issue posed a significant hurdle for studying star formation in the Galactic center as well as numerous other topics in which mid-infrared observations are crucial.

Recent observations from SOFIA were used to create high-quality mosaics of the most active star forming portions of the inner ~ 200 pc of our galaxy at 25 and 37 μm . These observations were taken as part of [SOFIA's first completed legacy program](#) which used the Faint Object infraRed CAmera for the SOFIA Telescope (FORCAST) instrument to image warm dust associated with star formation activity in the region. The SOFIA mosaics have an angular resolution of 2.3" and 3.4" for the 25 and 37 μm observations, respectively, and cover more than 99% of the hard saturated area in the corresponding Spitzer/MIPS mosaic. An overview paper meant to accompany the first survey data release has recently been accepted to ApJ and further details of the observations can be found therein.

One of the more interesting pieces in the overview paper considers a collection of isolated mid-infrared sources located between Sgr A and Sgr C. It is widely thought that the majority of star formation activity in the Galactic center is present at positive galactic longitudes; however, these sources at negative longitudes are curious because several are classified as young stellar object candidates in a prior survey. With the angular resolution provided by SOFIA/FORCAST (2.3" or 0.09 pc assuming a distance of 8 kpc), it is possible to study the morphology of these sources in detail which show a range from com-



Composite infrared image of the center of our Milky Way galaxy. Subset of the full image below centered on the Sgr B complex. (NASA/SOFIA/JPL-Caltech/ESA/Herschel)

compact bubbles to arc-like structures which could be indicative of a bow shock. Even more curious is an nearby extended 37 μm source, G359.645-0.081, which is unusually red and has prior Spitzer/IRS spectroscopic observations which indicate the presence of a hard ionizing source near this position. Further study is needed to better understand this complex, though we note that the source lacks a significant x-ray component, indicating it is unlikely a supernova remnant.

In addition to the collection of isolated sources discussed above, the overview paper features a number of other short segments on well-known regions within the survey area such as Sgr A, Sgr B, and Sgr C, as well as the

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Composite infrared image of the center of our Milky Way galaxy, spanning 600+ light-years across. New data from SOFIA taken at 25 and 37 μm , shown in blue and green, is combined with data from the Herschel Space Observatory, shown in red (70 μm), and the Spitzer Space Telescope, shown in white (8 μm). SOFIA's view reveals features that have never been seen before. (NASA/SOFIA/JPL-Caltech/ESA/Herschel)

Signatures of Star Formation in the Galactic Center

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Arched filaments HII region and the Sickle HII region. Finally, the survey team are currently working to produce high level data products including a point source catalog with color selected YSO candidates, a dust temperature map derived using the 25 and 37 μm observations, and an additional map that combines the SOFIA/FORCAST 25 μm and Spitzer/MIPS 24 μm data sets that will greatly expand the coverage area and dynamic range of both datasets. These data products will be made available to the broader SOFIA community as part of a later data release and will likely appear along with subsequent follow-up papers that are discussed in the survey overview paper. ■



Composite infrared image of the center of our Milky Way galaxy. Subset of the full image on page 9 centered on the Sgr C complex. (NASA/SOFIA/JPL-Caltech/ESA/Herschel)

A Magnetic Hourglass Detection for a Low-Mass Protostar

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function analysis was used to determine the ratio of the turbulent (B_t) to uniform (B_0) field. The result, $B_t/B_0 = 0.267 \pm 0.007$, confirms that the uniform component dominates. We can also derive the plane-of-sky projection of the field strength, $B_{\text{pos}} = 78 \mu\text{G}$. We also computed the gravitational-to-magnetic energy ratio, $\lambda = 0.95$. This is close to the energy balance regime ($\lambda = 1$), most likely arising from an average between the innermost part of the core, where gravity has already taken over leading to the protostar formation ($\lambda > 1.0$), and the outskirt medium,

which could be still in a subcritical state ($\lambda < 1.0$).

The SOFIA results indicate that IRAS 15398-3359 evolved in a highly magnetized environment and that the ordered magnetic field was preserved from cloud scales down to core scales. For the future, we plan to analyze spectroscopic observations already collected with the Atacama Pathfinder EXperiment (APEX) in order to derive the kinematic properties of the source. These data will help us answer key questions focusing on the interaction between the magnetic field structure and the gas dynamics. ■

The Optical Depth of [CII]: the Implications for Galaxies both Near and Far

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The complexity of the sources and their high optical depth required a more sophisticated approach in order to derive the physical properties of the gas. For these reasons, a double-layered model was developed, with an emitting background traced by the optically thin [^{13}CII], and an absorbing foreground traced by the difference between the [^{13}CII] and [^{12}CII] emission. We found that the background layer has high column density, much higher than expected due to the absorption effects. The ionized foreground is of unknown origin, but must be cold enough to absorb the

background radiation and not produce much emission.

The analysis presented here showed that the origin of [CII] emission is more complex than simple models might suggest. The structured line profiles and high optical depth visible in particular in the bright sources of strong [CII] emission in the Milky Way revealed substantially higher [CII] column densities than the ones estimated using an optically thin approximation. Physical parameters derived from the optically thin approximation should also be treated with caution. ■

SOFIA Reveals the Complex Nature of a ‘Simple’ Star Formation Tracer

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ratio $^{12}\text{CII}/^{13}\text{CII}$ varies over different velocity bins and is lowest at the peak of the line. Since there is little line-of-sight contamination towards the Large Magellanic Cloud, different velocities most likely correspond to different cloud components within the same region. Thus, they should have the same isotopic ratio. The second reason is that the fine-structure line from the neutral oxygen profile at $63\ \mu\text{m}$ also indicates self-absorption at the velocity where the intensity ratio of $^{12}\text{CII}/^{13}\text{CII}$ is lowest.

Optically thick [CII] emission is not limited to small-scale, extreme regions but turns out to be significant over an area of 4-by-4 sq pc in the Large Magellanic Cloud. This is consistent with the large-scale map obtained by upGREAT for the Orion Nebula. These results provide a warning to astronomers that the optical depth effect should not be ignored when using [CII] as a star-formation tracer. ■



Image of the Large Magellanic Cloud from the Hubble Space Telescope. (ESA/NASA/Hubble)

Occultation Confirms Haze in Pluto’s Atmosphere

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curve region near half-light was first modeled with previously-used clear atmospheric models. No significant pressure variation was identified between 2011 and 2015, providing information on how the atmosphere is effectively resupplied by nitrogen ice sublimation.

Neither a pure isothermal nor temperature-gradient atmospheric models resulted in good fits to the full 2015 SOFIA data. However, a thick, hazy region within the atmosphere produces an excellent fit to the entire dataset, including in and around the central flash, which is sensitive to lower altitudes of the atmosphere (where haze is presumed to be thicker).

In addition, a distinctive variation of residual flux across the different observed wavelengths was detected, which is strongly indicative of wavelength-dependent scattering by a haze component. Modeling of the residual flux gradient, assuming the haze composition, allowed scientists to constrain the characteristic haze particle size to $\sim 0.06\text{--}0.10\ \mu\text{m}$. This finding suggests that the haze must be replenished on short timescales, an important implication for understanding the photo-

chemistry of Pluto’s atmosphere.

The observations occurred just two weeks before the New Horizons spacecraft flew past the dwarf planet, providing researchers with multiple, nearly co-temporal datasets. Ultraviolet data from the spacecraft confirmed the existence of haze in the upper layers of Pluto’s atmosphere while infrared and visible light data from SOFIA confirmed the haze extending to atmospheric layers much closer to the surface.

This was SOFIA’s second Pluto occultation. The first set of observations, in 2011, confirmed that Pluto’s atmosphere was not collapsing as its eccentric orbit took it farther from the Sun. These observations predicted that the atmosphere would remain stable for the 2015 New Horizons flyby. Continued monitoring is necessary as the dwarf planet gets even further from the Sun, as numerous models predict Pluto’s atmosphere will at least decline if not vanish over the coming decades. The agreement between the flyby and SOFIA data where they overlap indicate that occultations continue to be an accurate method to remotely study Pluto’s atmosphere. ■

The Chemical Enrichment of the Universe

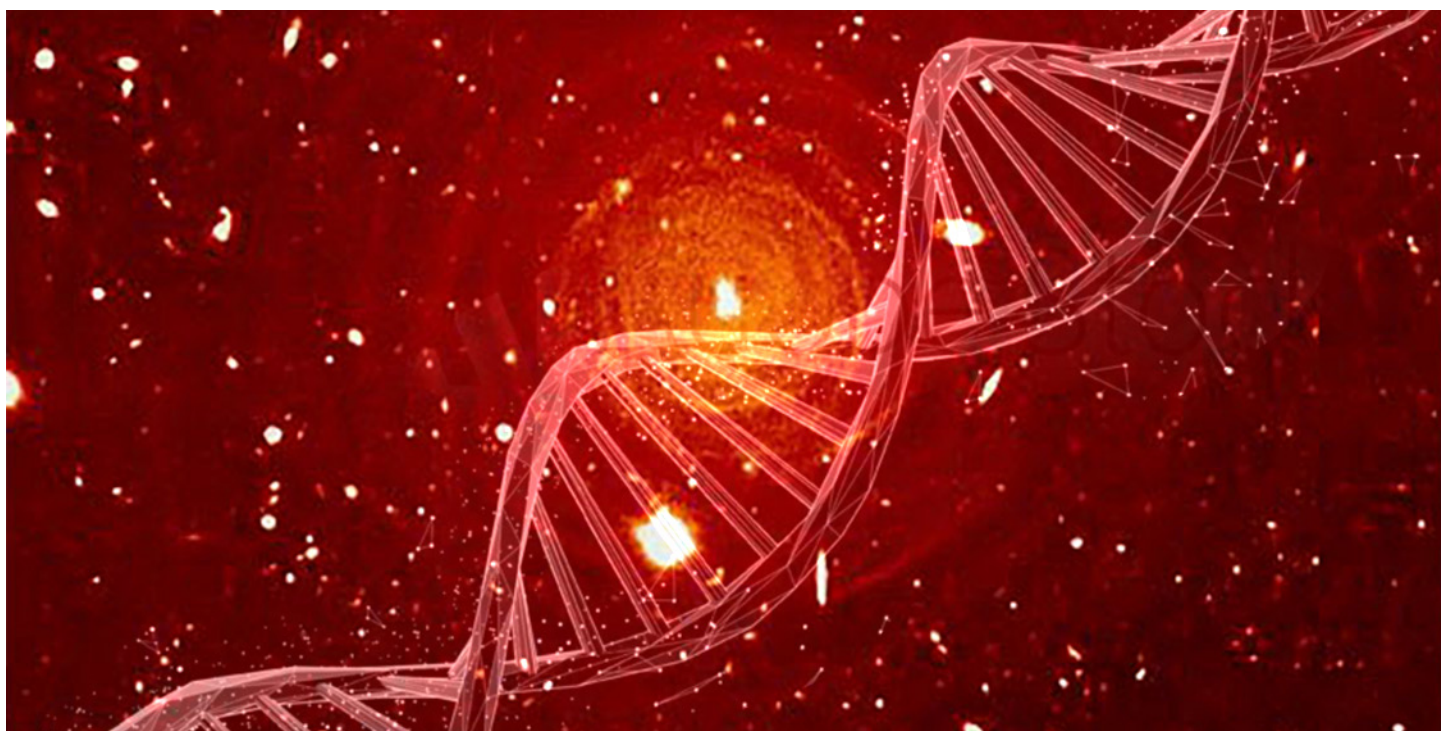
(continued from page 7)

pulsation mode. Mira variables are well-known for their long pulsation periods and strong amplitudes. Semi-regular variables always have weaker amplitudes, and they usually have shorter periods. The Mira variables, with their strong pulsations, are producing copious amounts of amorphous carbon dust, while the semi-regulars, particularly those classified as “SRb,” make much less dust, and it is mostly SiC.

The figure on page 7 shows this dichotomy. It plots the relative strength of the emission feature from SiC dust as a function of the [6]-[9] color, which is derived from the spectra and reddens as the star produces more amorphous carbon dust. In the Milky Way, the semi-regulars are cleanly separated from the Miras (at a [6]-[9] color of ~ 0.3), because they are making little or no amorphous carbon. As the total dust content increases, the strength of the SiC feature rises sharply, up to the transition to Mira variables. From that point to redder colors (higher x-axis values), the SiC feature decreases in relative strength as the total dust content rises. The carbon stars in the

Magellanic Clouds also show this behavior, with the semi-regular variables and Miras largely distinguishable by their [6]-[9] colors.

The different pulsational properties of Miras and semi-regulars are almost certainly responsible for the differences in the dust. Miras are experiencing radial pulsations in the fundamental mode, so that their entire atmosphere is moving inward and outward in unison, which will push gas further away from the photosphere and enhance the condensation of dust. Semi-regulars pulsate more weakly and often in overtone modes, which will result in lower pulsation velocities and smaller changes in radius. As a result, less gas will cool to temperatures low enough for dust to condense. These weak pulsations appear to be more conducive for the formation of just SiC. Once the star shifts to the fundamental mode and the pulsations grow sufficiently in amplitude, then amorphous carbon begins to form and the mass-loss process can take off. When this phase begins, the end of its life as a star is in sight. ■



Infrared spectra from SOFIA help reveal fundamental differences between the dust produced by two types of carbon-rich variable stars. Miras, well-known for their long pulsation periods and strong amplitudes, are producing copious amounts of amorphous carbon dust, while the semi-regulars form mainly SiC. These results help unravel the mystery of how the carbon produced inside stars gets out into the interstellar medium to provide not only the raw material for future generations of star formation, but also the methane in the atmospheres of planets and exoplanets as well as the DNA that forms the basis of life as we know it. (*Izan Leao; the Very Large Telescope/© Viks_jin - stock.adobe.com*)



Composite image of W51A, the largest star-forming region in our galaxy. Dozens of massive stars that are more than eight times the size of our Sun are forming there. They create intense radiation pressure that has pushed dust out of the star's natal cocoon, creating arcs and bubbles that glow brightly at infrared wavelengths of 37 and 70 μm , shown in green and red in this false color image. Hot gas remains inside these features, which is shown in the 20 μm view in blue. The background star field from Spitzer is shown in white. (NASA/SOFIA/Wanggi Lim, James De Buizer; NASA/JPL-Caltech)

SOFIA is a Boeing 747SP jetliner modified to carry a 106-inch diameter telescope. It is a joint project of NASA and the German Aerospace Center, DLR. NASA's Ames Research Center in California's Silicon Valley manages the SOFIA program, science and mission operations in cooperation with the Universities Space Research Association headquartered in Columbia, Maryland, and the German SOFIA Institute (DSI) at the University of Stuttgart. The aircraft is maintained and operated from NASA's Armstrong Flight Research Center, Building 703, in Palmdale, California.



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