# SOFIA Science

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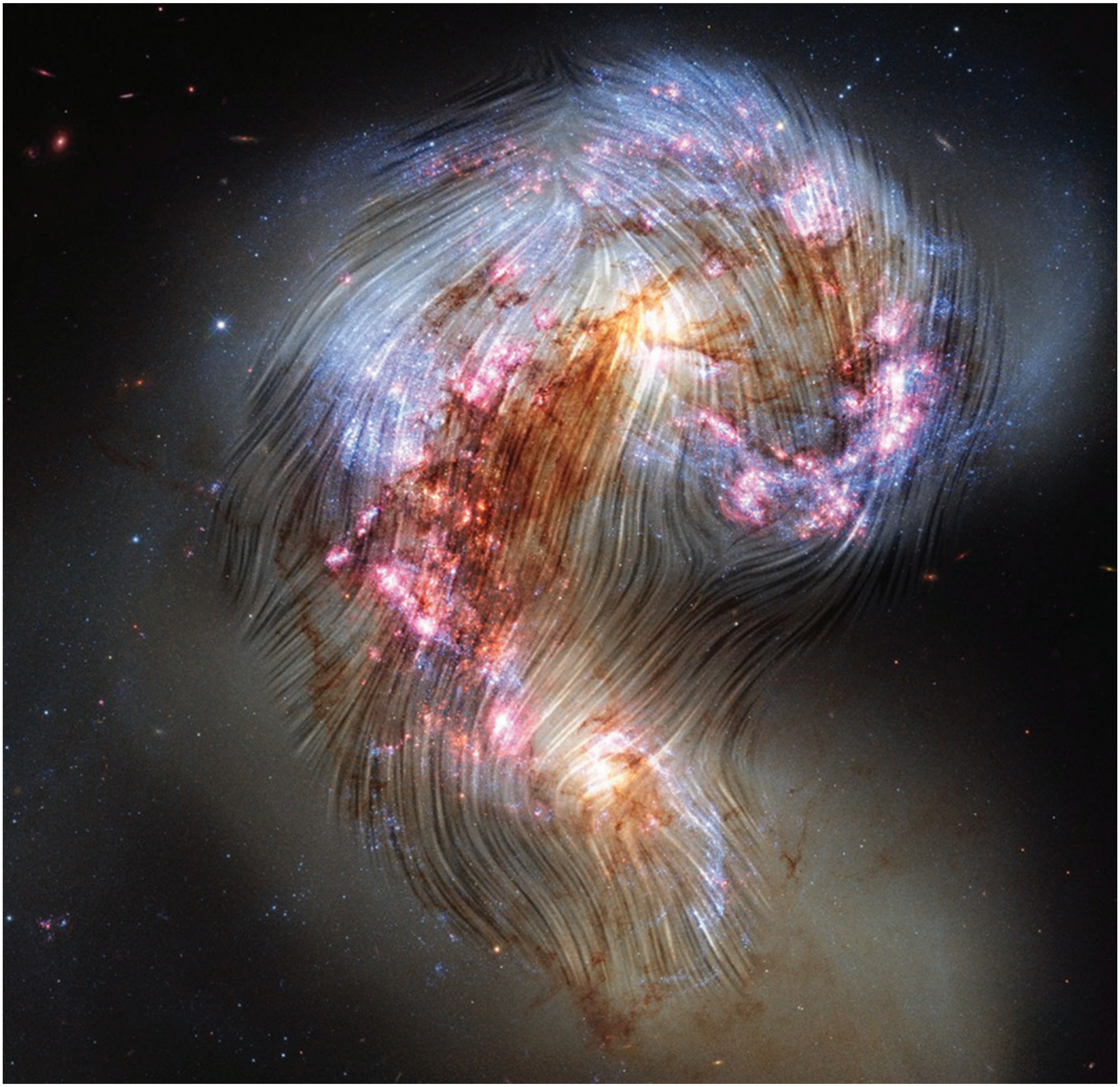
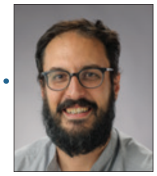


The magnetic fields of the closest merger of two spiral galaxies, the Antennae galaxies, as shown using observations by SOFIA/HAWC+. These observations show how mergers affect the B-fields in the gas within and around galaxies. The Antennae galaxies show ordered magnetic fields structures of ~8.9 kpc connecting both galaxies, and in the tidal tail toward the intergalactic medium. Both of the galaxy cores and the star-forming regions produce highly turbulent magnetic fields. The color image comprises HST observations using the filters F435W (blue), F550M (green), and a combination of F814W and F658N (red) by Withmore et al. 2010. The streamlines show the magnetic field orientations observed by SOFIA/HAWC+. *(ESA/Hubble/E. Lopez-Rodriguez)*. See page 2.

# Science Spotlight

Enrique Lopez-Rodriguez, *KIPAC/Stanford*
Joan Schmelz, *Universities Space Research Association*




# Magnetic Fields — A Ubiquitous Part of Galaxy Ecosystems

The evolution of galaxies is controlled by a delicate interplay between gravity, turbulence, feedback, dark matter, and magnetic fields. Most current empirical and theoretical approaches to understanding this interplay focus on all these factors — except magnetic fields. Magnetic fields are also needed to explain astrophysical phenomena such as star formation across cosmic time, accretion onto super massive black holes, and even planet formation. Thus, a self-consistent description of the interplay between the multi-phase interstellar medium and magnetic fields is needed to make progress on the fundamental processes controlling galactic evolution.

The Stratospheric Observatory for Infrared Astronomy (SOFIA) legacy program nicknamed SALSA aims to construct a comprehensive empirical picture of the magnetic field structure in the multi-phase interstellar medium of nearby galaxies. One of the main goals is to study the effect of the gas dynamics on the magnetic fields from hundred-pc-to-kpc scales in different types of galaxies.

The first data release of SALSA comprises multi-wavelength polarimetric observations from the High-resolution Airborne Wideband Camera Plus (HAWC+) of 14 nearby galaxies. These results are shaping, refining, and revolutionizing our understanding of extragalactic magnetism. Unquestionably, SALSA has shown that the magnetic fields are always present in the cold, dense interstellar medium of all galaxies.

SOFIA has discovered that:

- the magnetic field morphology is not necessarily the same in the diffuse and dense interstellar medium across the galactic disks of spiral galaxies like M51 and NGC 1068;
- the magnetic field following a warped molecular disk in the remnant of a merger galaxy like Centaurus A is being amplified and highly turbulent;

*(continued on page 8)*

## About this Spotlight

**Paper:** Extragalactic magnetism with SOFIA (SALSA Legacy Program) -- IV: Program overview and first results on the polarization fraction

**Authors:** E. Lopez-Rodriguez, S. A. Mao, R. Beck, A. S. Borlaff, E. Ntormousi, K. Tassis, D. A. Dale, J. Roman-Duval, K. Subramanian, S. Martin-Alvarez, P. M. Marcum, S. E. Clark, W. T. Reach, D. A. Harper, and E. G. Zweibel

**Reference:** 2022 ApJ 936 92.

## TABLE OF CONTENTS



## SOFIA SENIOR SCIENCE LEADERSHIP

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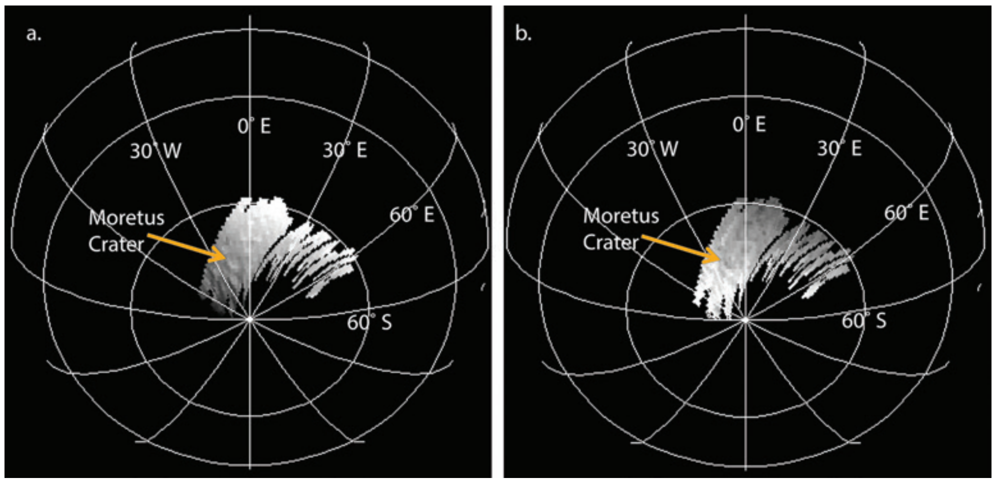
# Water on the Moon 2022

Following the first ever detection of the water molecule ($H_2O$) on the sunlit surface of the Moon, researchers using SOFIA have produced a regional map of the South Pole near Moretus crater. This map enables tests of various hypotheses for water formation and suggests that lunar surface water is created from pre-existing surface hydroxyl (OH) subsequently trapped in glass created during impacts.




Orthographically rectified images of average flux (a) and emission peak height (b). *(Honniball et al. 2022)*

The water molecule is a key compound for understanding the interaction of airless planetary surfaces with the space environment. In the contemporary era, water molecules have two principal styles of emplacement in the space weathering process: 1) they can be introduced directly into the lunar environment via micrometeorite impacts or 2) synthesized from solar wind hydrogen. While characterizing the behavior and origin of water is important to understanding the planetary process that is space weathering, it is of topical importance owing to the value of water for the progress of space exploration.

Previous investigations into understanding the distribution of water on the Moon made use of an absorption feature in reflectance spectra near 3 µm that is caused by stretching between hydrogen and oxygen atoms. This feature can be caused by both $H_2O$ and OH, making it impossible to distinguish between the two compounds. The 6 µm feature, on the other hand, is caused by bending of the H-O-H molecular bond and therefore unambiguously points to $H_2O$.

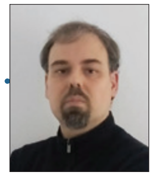
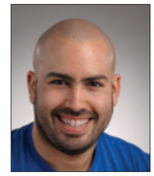
Due to its ability to fly over 99% of the Earth's atmosphere, SOFIA is one of the only observatories that can observe in the region near 6 µm. This, combined with the sensitivity of the Faint Object infraRed CAmera for the SOFIA Telescope (FORCAST) spectrometer, allows for the measurement of the strength of the 6 µm feature, which may vary across the surface due to changes in the water abundance.

The previous detection of molecular water by SOFIA was made by observing the same spot near the lunar Clavius crater multiple times. For this new observation, the telescope was moved by the width of the slit after every exposure, thus creating a spectral map of the surface. This demonstrated that FORCAST could be used as an imaging spectrometer. This was the first time a map like this was attempted by SOFIA, and it showed the

*(continued on page 9)*

## About this Spotlight

**Paper:** Regional Map of Molecular Water at High Southern Latitudes on the Moon Using 6 µm Data From the Stratospheric Observatory for Infrared Astronomy
**Authors:** C. I. Honniball, P. G. Lucey, A. Arredondo, W. T. Reach, and E. R. Malaret
**Reference:** Geophysical Research Letters, 49, e2022GL097786.

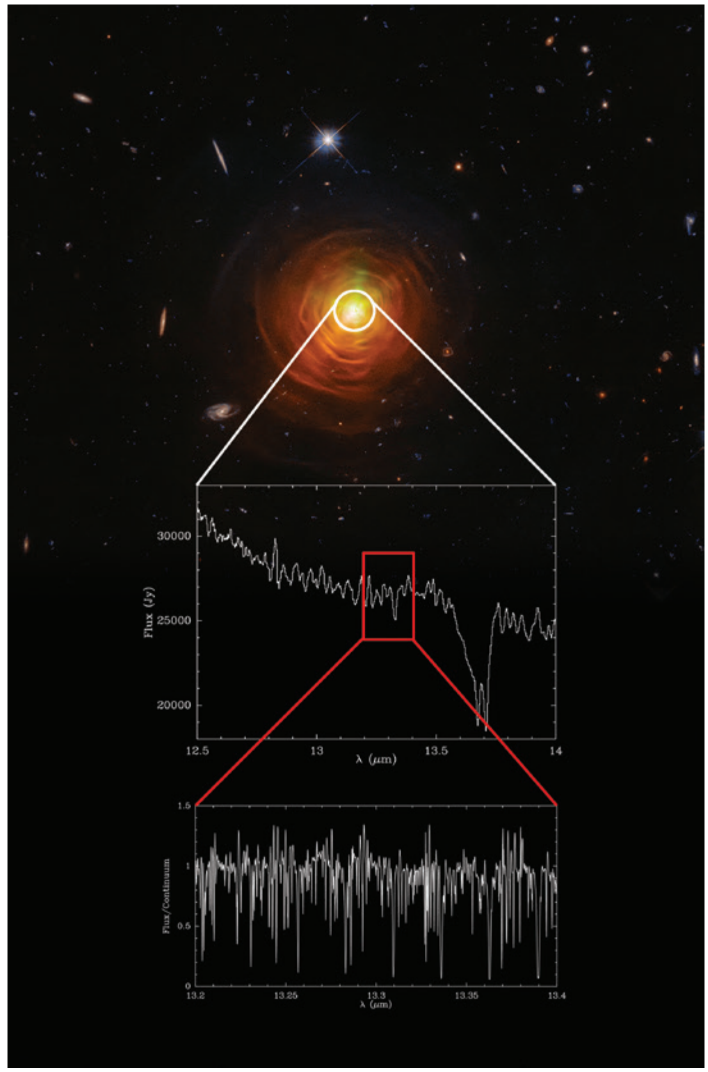

José Pablo Fonfría, *CAB, CSIC-INTA*
Ed Montiel, *Universities Space Research Association*
Joan Schmelz, *Universities Space Research Association*

# The SOFIA/EXES Mid-IR High Spectral Resolution Library

The ability of atoms to combine and form molecules is perhaps the most fundamental process leading to the evolution of life on Earth. This "molecular lifecycle" starts in space where giant molecular clouds gave birth to the first stars. As these stars approach the end of their lives, they swell to hundreds of times their initial size and shed their outer envelopes. As this circumstellar material cools, it creates an environment favorable to the formation of molecules. Mixing of these enriched envelopes with the interstellar medium enables the next generation of stars to form with the necessary ingredients for planets and possibly life.

The rotational spectra of most molecules are detectable with (sub)millimeter telescopes (e.g., SOFIA, IRAM 30m telescope, GBT, APEX) and interferometers (e.g., ALMA, SMA, NOEMA). These signals enable astronomers to determine abundances, temperature, and density, fundamental parameters required to model the environment of the emitting gas. However, symmetric molecules do not show rotational spectra and can, for the most part, only be observed in the infrared range. Examples include $H_2$, which accounts for most of the molecular mass in interstellar space, carbon dioxide, methane, and acetylene, all of which play important roles in astro-chemistry. Hence, observing their spectra helps us understand the evolution of stars, the universe, and life itself.

The sensitive, powerful instruments of JWST are already unveiling previously hidden astrophysical mysteries, but the science might be limited by the relatively low spectral resolution. This is a significant impediment in infrared astronomy because many molecules vibrate in a similar way so their spectral bands overlap. Consequently, molecules with the weakest bands, which are usually from the least abundant molecules, will be overlooked in low-spectral resolution observations. In this respect, the Echelon-Cross-Echelle Spectrograph (EXES) instrument on SOFIA is a valued partner for JWST. Its high-spectral resolution spectroscopy can separate the lines of the vibrational




Hubble Space Telescope image of IRC+10216 together with a small portion of the SOFIA/EXES high-resolution spectrum around 13.3 μm. The low-resolution spectrum taken with the Infrared Space Observatory is similar to the results expected from JWST. *(ESA/Hubble, NASA, and Toshiya Ueta (University of Denver), Hyosun Kim (KASI); Cernicharo et al., 1999; Montiel et al. (in prep); Fonfría et al (in prep))*

*(continued on page 9)*

Matthew Hankins, *Arkansas Tech University*

# The SOFIA/FORCAST Galactic Center Legacy Program

While the Milky Way galaxy is "average" in several regards, the environment in the central ~200 pc is unlike any other part of our galaxy. This region, known as the central molecular zone (CMZ), has high molecular gas densities, high gas and dust temperatures, significant turbulence, and a strong gravitational potential well, which combine to create a very unusual and complex star formation environment that has more commonalities with actively star forming galaxies compared to the Milky Way as a whole (Mills 2017 and references therein). Our relative proximity to the CMZ provides a unique opportunity to study star formation on size scales that are simply inaccessible in other galaxies.

However, in stating these similarities, there is an important difference that should be considered, because the CMZ is relatively inefficient at forming stars. In fact, the observed global star formation rate in this region is deficient by an order of magnitude or more compared to theoretical expectations based on its molecular gas reservoir (Longmore+ 2013). This is a significant conundrum in our understanding of this Galactic Center (GC), and potentially has broad implications for observational star formation tracers that are used to study other galaxies.

In order to study this star formation quandary in further detail, one of SOFIA's first Legacy Programs targeted infrared bright regions within the GC to conduct a census of recent high-mass star formation.

The survey has produced high quality mosaics of the GC at 25 and 37 µm using the Faint Object infraRed CAmera for the SOFIA Telescope (FORCAST) instrument. The SOFIA/FORCAST observations have an angular resolution of 2.3″ and 3.4″ for the 25 and 37 µm observations, respectively. The spatial resolution provided by SOFIA/FORCAST — 2.3″ or 0.09 pc, assuming a distance of 8 kpc — is key for tracing warm dust associated with young stellar objects which might be confused with nearby molecular cloud material in lower resolution maps.

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)*

Additionally, the improved spatial resolution allows for morphology studies for a variety of objects in the region, ranging from compact bubbles to arc-like structures which could be indicative of a bow shock.

These SOFIA/FORCAST observations cover many important regions within Sagittarius A, B, and C which were badly saturated in archival Spitzer/MIPS 24 µm observations. Previous studies of these regions at about 20 µm relied on earlier observations from the Midcourse Space Experiment, which are much lower spatial resolution — about 20″ at 21.3 µm — compared to the SOFIA/FORCAST GC Legacy mosaics. The recent survey overview paper (Hankins+2020) provides researchers with a useful guide to the observations and survey mosaics in these and other regions of interest within the GC, including the Arched Filaments HII region and the Sickle HII region. Additionally, there are numerous lesser-known sources that show spatially resolved structures that are visible for the first time in the SOFIA/FORCAST mosaics.

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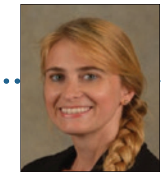
## Science Spotlight



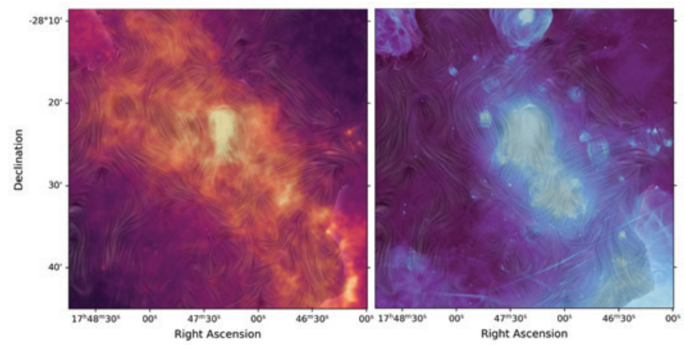
Natalie Butterfield, *National Radio Astronomy Observatory*

# The Galactic Center Magnetosphere

The role that magnetism plays in the central engines of galaxies remains an open question. Our own Galactic Center (GC) exhibits phenomena and conditions that are rare and extreme within the Milky Way, and hence offers the closest look at the physics of these unique regions of spiral galaxies. One of the most striking features of the GC is the existence of the so-called "nonthermal filaments" (NTFs; Yusef-Zadeh, Morris and Chance, 1984), large, filamentary structures of radio synchrotron emission that highlight the GC's magnetic field in regions of hot gas. Most of these structures are perpendicular to the orientation of the galactic plane, indicating that the field in the hot gas within the GC is poloidal.

Molecular gas within a few hundred parsecs (pc) of the GC, known as the Central Molecular Zone (CMZ), also exhibits extreme characteristics that are typically only found in intense star-forming regions with high magnetic field strengths (≥100$\mu$G) and molecular densities ($10^3$–$10^6$ cm$^{-3}$). These gas and dust particles in the CMZ tend to coalesce into a large-scale structure with a radial distance 50–100 pc from the supermassive black hole, Sgr A*. As these clouds traverse around Sgr A*, they transport mass and energy in their orbital motion and could be interacting with and influencing the magnetic fields in this region of the galaxy. Two outstanding questions are of interest. First, *how does the magnetic field in the cooler, denser, dust-dominated phases of the GC relate to the poloidal field present in the ionized phase?* Second, *does such a connection relate to the physical mechanism responsible for the formation of NTFs?* Measurement of polarized emission from magnetically-aligned dust grains using SOFIA/HAWC+ provides a mechanism for studying the magnetic fields in the cool dust of the CMZ.

The FIREPLACE (Far-InfraRed Polarimetric Large Area CMZ Exploration) Legacy Survey is designed to address these questions. The FIREPLACE survey measures the polarization at 214 µm across the entire CMZ at unprecedented resolution (<20"; 0.7 pc). This program is complementary to the SALSA Legacy program in which magnetic fields in external galaxies are measured and characterized (Lopez-Rodriguez+2022). A pilot program (0.5 degrees around the Sgr B complex) for the FIREPLACE survey was undertaken in Fall 2021 and provides the first insight into these questions.




Magnetic fields inferred from the FIREPLACE pilot study are shown superposed on Herschel 250 µm data (left) and MeerKAT 1 GHz data (right). Non-thermal filaments (NTFs) that run perpendicular to the galactic plane can be seen in the lower right part of the image on the right. *(Left: Herschel/SPIRE/Molinari et al., background; Butterfield et al., magnetic fields; Right: MeerKAT/Heywood et al., background; Butterfield et al., magnetic fields)*

The initial magnetic field vectors from the FIREPLACE pilot program are shown as line integral contours (Leedom & Cabral 1994) in Figure 1 above, superposed on both Herschel/SPIRE 250 µm thermal dust emission (Molinari+2011) and on 1 GHz emission from MeerKAT (Heywood+2022), which is dominated by synchrotron emission at this low frequency. The galactic plane is oriented at a slight NW-SE diagonal in Figure 1, and a few NTFs can be seen in the lower right of the MeerKAT image (right panel of figure). The field traced by the HAWC+ polarization measurements is complex. There are regions where the field structure follows the far-infrared morphology, those where the field is parallel to the plane, and those where it is perpendicular.

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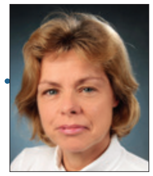
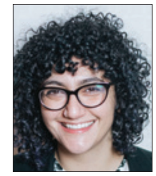
## Science Spotlight



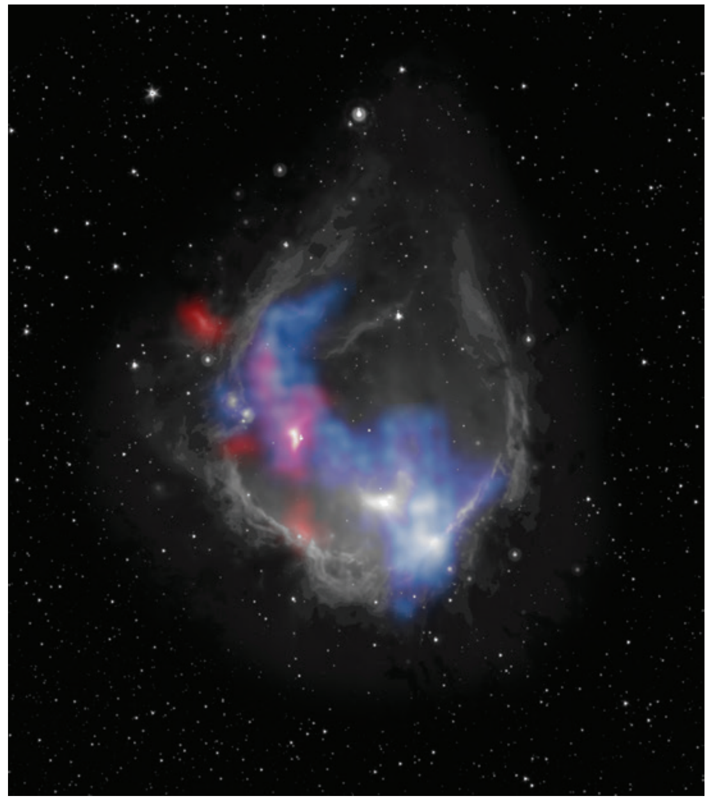


Nicola Schneider, *University of Cologne*
Alexander Tielens, *Leiden University*
Anashe Bandari, *Universities Space Research Association*

# The SOFIA Legacy Program Feedback

The interaction of massive stars with their environments regulates the evolution of galaxies through a process called feedback. Mechanical input by massive stars stirs up the interstellar medium, greatly influencing the star formation efficiency of molecular clouds as, on the one hand, this disperses star forming molecular cloud cores and, on the other hand, it creates dense shells of swept up gas that are prone to gravitational collapse. In addition, the radiative energy input by massive stars creates ionized gas regions surrounded by dense photo-dissociation regions, and the spectral characteristics of these regions dominate the emission of galaxies. This gas heating also controls the cloud and intercloud phases of the interstellar medium and thereby the overall structure of the interstellar medium.

The high sensitivity, high spectral resolution, and fast mapping speed of the German REceiver for Astronomy at Terahertz Frequencies (upGREAT) heterodyne instrument on SOFIA provides a unique tool to study this feedback of massive stars on their surrounding medium. This instrument can probe the dominant cooling line of moderate density gas illuminated by strong far-UV radiation fields, allowing us to quantify the relationship between the energy injected by star formation activity and the feedback processes involved.



Composite image of the nebula RCW 120. The newly formed O star is moving at ~4 km/s toward the South, sweeping up a dense shell of gas with a bow shock at the bottom and broken open at the top. The ring-shaped clouds around the nebula were detected by the Spitzer Space Telescope. SOFIA measured the glowing gas shown in red and blue to study the nebula's expansion speed and determine its age. The blue and red gas represent, respectively, emission at velocities between -23 and -16 km/s, expanding in the direction toward Earth, and -1 and +3 km/s, expanding away from Earth. The expansion of this shell has triggered the birth of stellar neighbors at breakneck speeds – and reveals that the nebula is younger than previously believed. *(NASA/JPL-Caltech/SOFIA)*

By mapping the [CII] 158 µm line in molecular clouds, the FEEDBACK Legacy Program has measured this energetic interaction in 11 regions of massive star formation. The sample spans a range in stellar characteristics from

*(continued on page 11)*

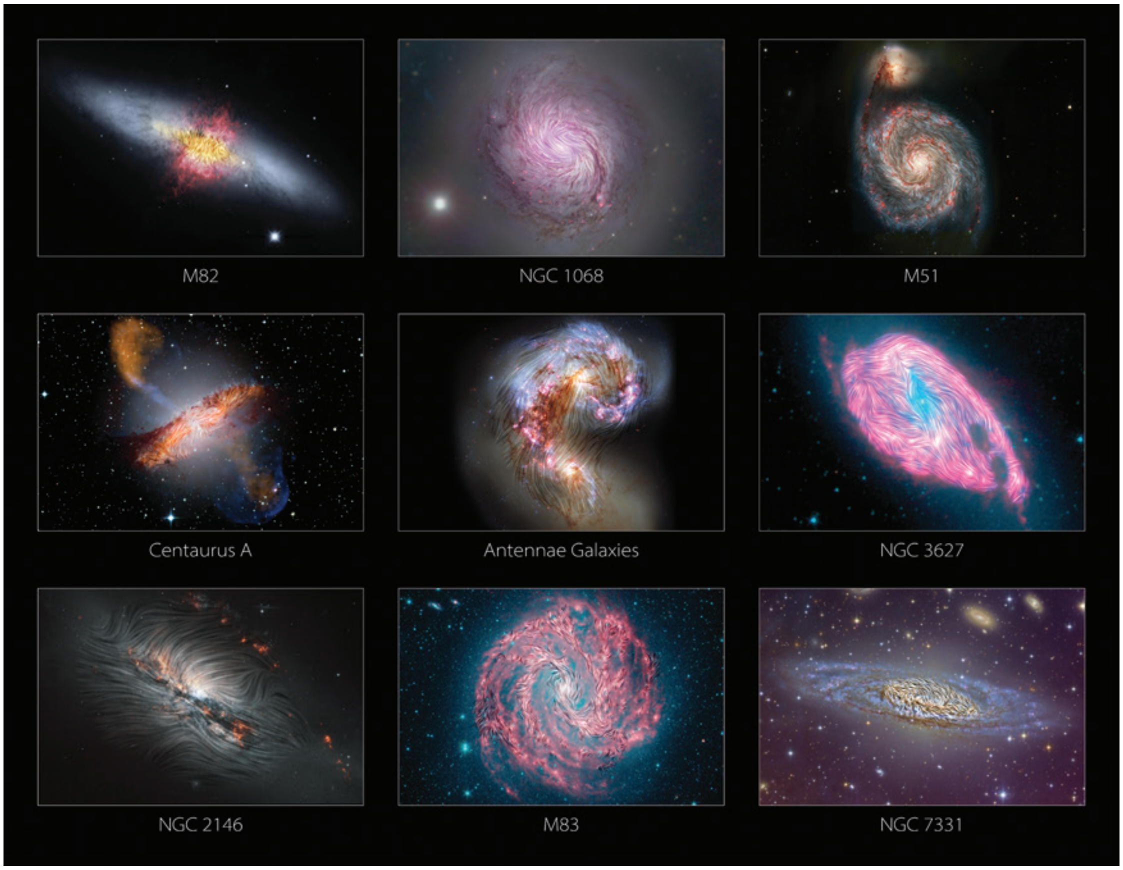
### About this Spotlight

**Paper:** FEEDBACK: a SOFIA Legacy Program to Study Stellar Feedback in Regions of Massive Star Formation
**Authors:** N. Schneider, R. Simon, C. Guevara, C. Buchbender, R. D. Higgins, Y. Okada, J. Stutzki, R. Güsten, L. D. Anderson, J. Bally, H. Beuther, L. Bonne, S. Bontemps, E. Chambers, T. Csengeri, U. U. Graf, A. Gusdorf, K. Jacobs, M. Justen, S. Kabanovic, R. Karim, M. Luisi, K. Menten, M. Mertens, B. Mookerjea, V. Ossenkopf-Okada, C. Pabst, M. W. Pound, H. Richter, N. Reyes, O. Ricken, M. Röllig, D. Russeil, Á. Sánchez-Monge, G. Sandell, M. Tiwari, H. Wiesemeyer, M. Wolfire, F. Wyrowski, A. Zavagno, and A. G. G. M. Tielens
**Reference:** 2020 PASP 132 104301.

# Magnetic Fields — A Ubiquitous Part of Galaxy Ecosystems

(continued from page 2)

- the galactic magnetic field can be dragged away permeating the intergalactic medium via galactic winds like those in the starburst galaxy M82; and
- a magnetically-driven flow feeds the super massive black hole of the active nucleus in NGC 1097.




The magnetic fields of spiral (M51, M83, NGC 3627, NGC 7331), starburst (M82, NGC 2146), active galactic nuclei (NGC 1068 and Centaurus A), and merging (Antennae galaxies) galaxies obtained by SALSA (Survey of extragALactic magnetiSm with SOFIA). Results are published in The Astrophysical Journal (SALSA IV: Lopez-Rodriguez et al.). *(M82: NASA/SOFIA/E. Lopez-Rodriguez; NASA/Spitzer/J. Moustakas et al.; NGC 1068: NASA/SOFIA; NASA/JPL-Caltech/Roma Tre Univ.; M51: NASA, the SOFIA science team, A. Borlaff; NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA); Centaurus A: Optical: European Southern Observatory (ESO) Wide Field Imager; Submillimeter: Max Planck Institute for Radio Astronomy/ESO/Atacama Pathfinder Experiment (APEX)/A.Weiss et al.; X-ray and Infrared: NASA/Chandra/R. Kraft; JPL-Caltech/J. Keene; SOFIA; Antennae galaxies: ESA/Hubble & NASA/E. Lopez-Rodriguez; NGC 3627: NASA/JPL-Caltech/R. Kennicutt (University of Arizona) and the SINGS Team/E. Lopez-Rodriguez; NGC 2146: ESA/Hubble & NASA/E. Lopez-Rodriguez; M83: NASA/JPL-Caltech/E. Lopez-Rodriguez; NGC 7331: Vicent Peris, CC BY-SA 2.0/E. Lopez-Rodriguez*

The new release presents a statistical analysis of galaxies as a function of wavelength, inclination, and galaxy type. Using the dependency of the state of polarization and the physical properties of the interstellar medium in spiral galaxies, this work is able to identify the ordered magnetic field associated with shear or compression along the spiral arms and the random magnetic field associated with star formation regions across the galaxy disks. These results allow us to understand the mechanisms responsible for the amplification and generation of magnetic fields in galaxy evolution.

Although magnetic fields are found in all galaxies, there is not yet a comprehensive theory about how the present-day galactic magnetic fields originate. The results presented in this release can be used to understand how magnetic fields permeate the intergalactic medium at early stages of the universe, investigate the processes of star formation and the assembly of giant molecular clouds in galaxies, and refine dynamo theories responsible for galaxy formation.

The current combination of the magnetic fields in the cold, dense regions via far-infrared polarimetric observations and warm, diffuse regions via radio polarimetric observations provide the ground truth to refine theoretical models. Future far-infrared polarimetric space missions will be required to perform a complete census of magnetic fields in galaxy evolution. ■

## The SOFIA/EXES Mid-IR High Spectral Resolution Library

*(continued from page 4)*

bands and reveal the weak signals of low-abundance molecules that would otherwise be hidden among a forest of stronger lines from other species.

The EXES Legacy program was designed to create a library of these weaker lines so they could be incorporated into the JWST spectral fitting software, substantially enhancing the scientific value of the JWST molecular observations. Initially more ambitious, the program was tailored (due to the end of SOFIA mission) to include the three most promising sources: the hot cores, NGC 7538 IRS1 and AFGL 2136, as well as the asymptotic giant branch star IRC+10216. The observations included most of the mid-infrared range (from 5 to 28 µm) with a spectral resolution better than 6 km/s. This high spectral resolution can not only isolate molecular lines but also resolve their profiles making it possible to analyze in detail the gas kinematics in the layers of the emitting molecules.

Analysis of the IRC+10216 observations is already underway. IRC+10216 is a carbon-rich, evolved star located 120 pc from Earth with a dense circumstellar envelope composed of dust grains and molecular gas. To date, there are 298 different molecular species detected in space, and 95 of them are seen towards IRC +10216. Of particular importance are the spectral bands around 6.3 µm and 15.0 µm, which are unobservable by ground-based telescopes due to the presence of atmospheric water and carbon dioxide, respectively. Likewise, the short- and long-wavelength edges of the covered range were barely explored in the past and could reveal previously undetected molecules.

A detailed analysis of the thousands of molecular lines in the observed spectral range is on-going. Many lines, primarily beyond 7 µm, show P-Cygni profiles (features with emission and absorption components) that belong to low-excitation, vibrational bands of the so-called parent molecules that form at the stellar photosphere or very close to it. The rest of the lines are seen only in absorption and are either produced by molecules that form in the intermediate and outer layers of the envelope, or are lines of highly excited vibrational bands.

The observations of the EXES Legacy program will help improve our understanding of the spectroscopically rich mid-infrared region. In addition, the identification and analysis of these lines is crucial to refine the circumstellar chemistry models that will help interpret JWST data and increase our understanding of how matter behaves in the astrophysical environments where molecules form. ■

## Water on the Moon 2022

*(continued from page 3)*

possibility that SOFIA observations can be used to measure how the surface water changes.

The estimated abundance of water based on the strength of the emission feature is a couple hundred parts per million, in agreement with the amount found in the nearby Clavius crater. This amount of surface water probably cannot be freely exchanging with the Moon's tenuous exosphere because it would require much more water in the exosphere than has been measured by spacecraft.

The measurements also point to an inverse correlation with surface temperature, where colder regions have greater abundance. The distribution of water is consistent with derivation of water from pre-existing hydroxyl subsequently trapped in impact glass, provided hydroxyl increases with latitude as some models and measurements suggest.

Further observations with SOFIA have created water maps of various regions on the Moon, including interesting geologic features such as craters and pyroclastic flows. Observations of multiple latitudes at multiple lunar times of day will constrain hypotheses about the origin, distribution, and evolution of lunar water. These observations will be critical for future NASA missions such as the VIPER lunar rover and the Artemis program that will return humans to the Moon by 2024. ■

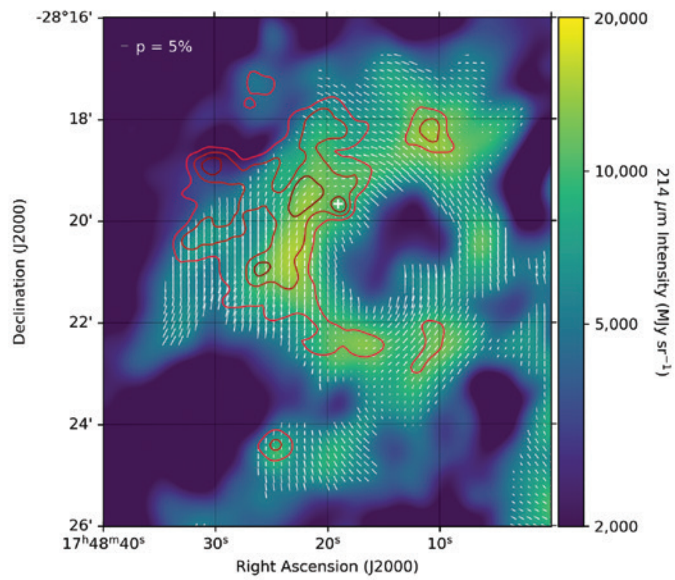
# The Galactic Center Magnetosphere

*(continued from page 6)*

A quantitative analysis reveals a bimodal distribution of magnetic field directions in which there are enhancements in the distribution of field directions parallel and perpendicular to the galactic plane (Butterfield+2022). The parallel field vectors are more evident at higher far-infrared intensities (presumably corresponding to higher density regions) and likely result from the shearing of the field by the gravitational motion of the cloud clumps in their orbits around the CMZ. At lower densities, the field direction distribution has an increased contribution in the direction perpendicular to the plane, which matches the direction of the field traced by the NTFs. The idea of a complex field in the dust component of the GC has been posited (Chuss+2003), but FIREPLACE has an increase of coverage of more than two orders of magnitude from previous ground-based measurements at comparable angular resolution, enabling the statistical testing of this hypothesis.

In addition to studies of the large-scale field, the FIREPLACE pilot program has enabled the investigation of individual clouds in the CMZ region. M0.8-0.2, shown both in Figures 1 (page 6) and 2 (right), has a structure in which the magnetic field is predominantly azimuthal with respect to a ring-like morphology. We interpret this structure to be an expanding shell in which the ambient field is stretched and compressed. This may be a result of feedback — we identify a candidate source (shown as a white "+" in Figure 2) that may be responsible.

The magnetic field directions inferred for M0.8-0.2 are most clear in Figure 2, where the azimuthal orientation of the magnetic field can be readily seen. Using the Davis-Chandreshkar-Fermi Technique, we have estimated field strengths of 200-400 microGauss across the source. The dust associated with M0.8-0.2 is cool (T~15K; Molinari+2011) and no significant X-ray and very faint 1 GHz synchrotron emission is seen.




SOFIA/HAWC+ 214 μm emission of the Ring (M0.8-0.2), overlaid with the magnetic field directions (white pseudovectors). The white "+" shows the location of a point source that may be responsible for driving the expansion. Red contours show the 3mm (90 GHz) MGPS data at 10 sigma, 15 sigma, 20 sigma levels (0.5 mJy/beam). The magnetic field geometry is suggestive of a field that is compressed by the expansion of a shell of material. This expansion/compression interpretation implied by the magnetic field measurements is consistent with molecular gas kinematics (e.g., Mills & Battersby 2017). *(Butterfield et al.)*

The pilot study for FIREPLACE provides a proof-of-concept for making large polarimetric maps with SOFIA. Once completed, FIREPLACE will provide data across the entirety of the CMZ, an area corresponding to 1.5 degrees in galactic longitude (approximately 250 pc at the GC distance, 8 kpc). This will provide tens of thousands of Nyquist-sampled measurements with an angular resolution of 20", covering all of the major structures of the CMZ. ■

# The SOFIA/FORCAST Galactic Center Legacy Program

*(continued from page 5)*

The Legacy Program team is in the process of completing the survey catalog and expect it to be released in early 2023. The team is also creating updated survey mosaics which combine later SOFIA/FORCAST observations taken in SOFIA Cycles 8 and 9 with the original survey that was observed in Cycle 7. These additional observations increase the original survey area for sources of interest near Sgr B and C and provide significant added legacy value to the data for future research. Interested researchers can access the SOFIA/FORCAST Galactic Center survey data on the IRSA SOFIA portal. ■

# The SOFIA Legacy Program Feedback

*(continued from page 7)*

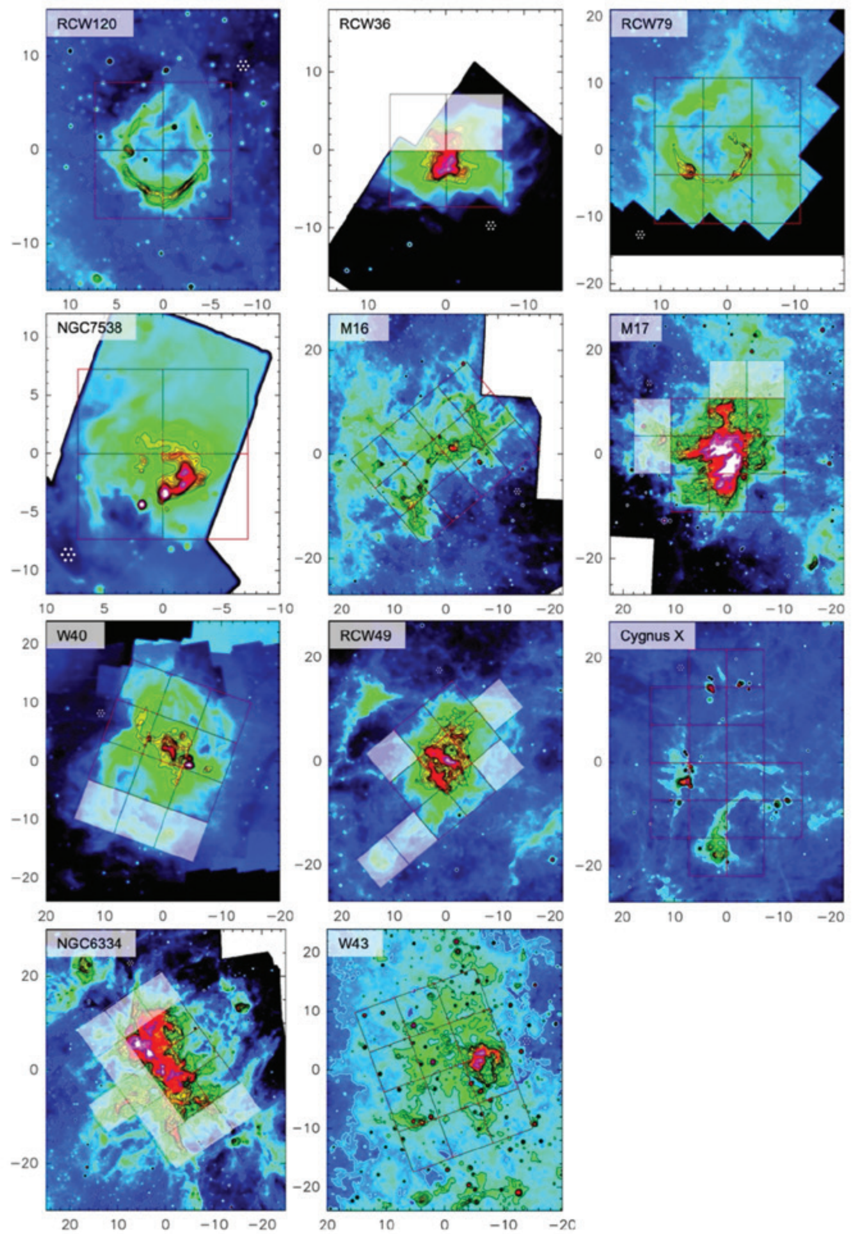
regions dominated by single O stars to clusters containing dozens of O and Wolf-Rayet stars, in evolutionary age from hundreds of thousands to several million years, and in star formation activity from isolated O star birth-sites to massive, star-forming, giant molecular cloud complexes and starburst environments. Figure 1 (page 7) summarizes the targeted sources and the areas surveyed. The data contain fully sampled maps of [CII] 1.9 THz for each source at high spatial (14”) and spectral (0.3 km/s) resolution. All data is available through the IRSA SOFIA Archive.

In a study of the Orion molecular cloud, FEEDBACK surveyed the bubbles blown by θ1 Orionis C, Nu Orionis, and 42 Orionis (e.g. associated with M42/the Veil Nebula, M43, and NGC 1977), revealing the large amounts of kinetic and thermal energy in the warm swept-up neutral shells.

Another region FEEDBACK studied was RCW 120, a nearby (~1.7 kpc) HII region with a physical diameter of ~4.5 pc. This region is ionized by a single O8V star, moving at about 4 km/s through the molecular cloud, with a fast stellar wind that has created a bow shock and swept up a dense, fragmented shell, the site of triggered star formation. FEEDBACK’s [CII] 1.9 THz observations reveal that this shell contains about 500 solar masses of neutral gas expanding at 15 km/s. The kinetic energy involved in the shell’s expansion represents a major fraction of the mechanical energy injected by the star over its 150,000-year lifetime through its stellar wind.

The FEEDBACK survey has revealed that efficient conversion of stellar wind mechanical energy into kinetic and turbulent motion of surrounding atomic and molecular gas is a common characteristic during the early stages of HII region evolution, but this conversion efficiency decreases with age as bubbles burst open and vent the over-pressurized hot gas into their environment.

Combined with ancillary data, FEEDBACK’s [CII] maps can be used to quantify the physical conditions in the dense, warm shells swept up in photodissociation regions. ■




Feedback source sample. The red boxes outline the tiles proposed to be observed for each source. The slightly opaque ones were not observed. Colored background: The IRAC 8 μm map of the sources tracing the PDRs in these regions convolved to the 14” upGREAT beam. Contours are predicted [CII] 1.9 THz integrated line intensity based upon the [CII]-8 μm relation derived for L1630, Orion, and 30 Dor. Contour levels are: white dashed (50 K km/s), white (100 K km/s), black (150(50)400 K km/s), red (500 K km/s), blue (1000 K km/s). Box units are in arcmin. The upGREAT 7 beam pattern is plotted alongside the outlined area in each box, illustrating that much finer detail than visible in these images can be traced. *(Robert Simon, University of Cologne)*

# SOFIA Transition from Operations to an Orderly Closeout

SOFIA ended science flight operations on October 1, 2022, and the SOFIA Science Center ends operations on September 30, 2023. Many resources for SOFIA users will be maintained beyond that date, to support the astronomy community and in particular facilitate archival data research. Here is a summary of what the SOFIA community can expect during the transition time and beyond.

1. **Helpdesk:** SOFIA's helpdesk service (help_desk@sofia.usra.edu) is supported at the SOFIA Science Center. In addition to general inquiries, this service can be used for users to get in-depth support from SOFIA instrument scientists on questions pertaining to data. After that service closes in 2023, general inquiries can be addressed to the IRSA helpdesk service: irsasupport@ipac.caltech.edu.

2. **Website:** the SOFIA website sofia.usra.edu is currently active. In 2023, the website will close and redirect to a dedicated page on the IRSA website: https://irsa.ipac.caltech.edu/Missions/sofia.html. This page will host all documents, tutorials and general information for archival data users.

3. **Data Archive:** SOFIA's archival data is and will continue to be hosted at IRSA: https://irsa.ipac.caltech.edu/applications/sofia. Note that access to the Data Cycle System Server (https://dcs.arc.nasa.gov/) will eventually be restricted.

4. **Press office:** press releases, blog posts and social media campaigns are currently produced by SOFIA Science Center. Support will be transferred to the Ames Office of Communications in 2023.

5. **Grant Support:** the administration of awarded grants and associated support will be managed by USRA up until September 2024. Contact: emonroy@usra.edu.

6. **Research Funding:** eligible researchers using SOFIA archival data can apply for funding through NASA's Astrophysics Data Analysis Program (ADAP).

SOFIA was a joint project of NASA and the German Space Agency at DLR. DLR provided the telescope, scheduled aircraft maintenance, and other support for the mission. NASA's Ames Research Center in California's Silicon Valley managed the SOFIA program, science, and mission operations in cooperation with the Universities Space Research Association, headquartered in Columbia, Maryland, and the German SOFIA Institute at the University of Stuttgart. The aircraft was maintained and operated by NASA's Armstrong Flight Research Center Building 703, in Palmdale, California. SOFIA achieved full operational capability in 2014 and concluded its final science flight on Sept. 29, 2022.


SOFIA — Stratospheric Observatory for Infrared Astronomy

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