# SOFIA Science

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Magnetic field streamlines detected by SOFIA are shown over an image of the Whirlpool galaxy from NASA's Hubble Space Telescope. See Science Spotlight, page 3. *(NASA, the SOFIA science team, A. Borlaff; NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA))*

The Stratospheric Observatory for Infrared Astronomy, or SOFIA, observes the solar system and beyond, gathering data to investigate fundamental astrophysical phenomena such as star birth and death, formation of new solar systems, organic compounds in space, nebulae and the ecosystems of galaxies, celestial magnetic fields, black holes at the center of galaxies, as well as planets, comets, and asteroids in our solar system.

SOFIA's instruments operate in the near-, mid-, and far-infrared wavelengths, each suited to studying a particular phenomenon. Flying into the stratosphere at 38,000–45,000 feet puts SOFIA above 99 percent of Earth's infrared-blocking atmosphere, letting astronomers study the solar system and beyond in ways that are not possible from the ground.

This edition of the SOFIA Science newsletter highlights recent SOFIA science results, covering a range of topics from magnetic fields to Earth's atmosphere.

SOFIA offers the following tools and documentation to facilitate the proposal process, available at www.sofia.usra.edu.

## 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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# Magnetic Chaos Hidden Within the Whirlpool Galaxy

Hidden deep inside their spiral structure, an invisible force is affecting the evolution of galaxies — magnetic fields. Strong enough to regulate star formation and even drive gas into a supermassive black hole, magnetic fields might be one of the most important factors influencing how spiral galaxies evolve. In theory, the field could be affecting the global kinematics of the gas, modifying the rotation curve, and the redistribution of dense clouds of gas as they condense into stars. As a consequence, the magnetic fields might indirectly be forcing stars to migrate radially in the galactic disk. To detect these effects, it is necessary to map the shape of the magnetic fields in the cold, dense molecular clouds. However, traditional observations of magnetic fields made with radio telescopes are only sensitive to the diffuse interstellar gas that surrounds these star-forming regions, far away from where these fundamental effects might be taking place.

Thanks to SOFIA, scientists have finally been able to observe the morphology of the magnetic field inside the molecular gas of the grand design Whirlpool galaxy (also known as Messier 51). The High-resolution Airborne Wideband Camera (HAWC+) is able to map the magnetic fields deep in the cold, dark molecular clouds. The research team then compared these results with the magnetic field maps of the diffuse gas made with the Very Large Array in New Mexico and the Effelsberg radio telescope in Germany.

## About this Spotlight

**Paper:** Extragalactic Magnetism with SOFIA (Legacy Program) -- I: The magnetic field in the multi-phase interstellar medium of M51
**Authors:** A. S. Borlaff, E. Lopez-Rodriguez, R. Beck, R. Stepanov, E. Ntormousi, A. Hughes, K. Tassis, P. M. Marcum, L. Grosset, J. E. Beckman, L. Proudfit, S. E. Clark, T. Díaz-Santos, S. A. Mao, W. T. Reach, J. Roman-Duval, K. Subramanian, L. N. Tram, E. G. Zweibel, SOFIA Legacy Team
**Reference:** 2021 ApJ 921 128.

Magnetic field streamlines detected by SOFIA are shown over an image of the Whirlpool galaxy from NASA's Hubble Space Telescope. For the first time, SOFIA's infrared view shows that the magnetic fields in the outer arms do not follow the galaxy's spiral shape and are instead distorted. The intense star formation activity in these regions, shown in red, may be causing the chaos, along with the forces from the yellow neighboring galaxy tugging on one of the spiral arms. *(NASA, the SOFIA science team, A. Borlaff; NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA))*

The magnetic field lines in the inner region of the Whirlpool galaxy show a regular spiral structure, but field lines in the molecular clouds decouple from those of the diffuse gas in the outskirts — closer to the companion galaxy Messier 51b. The field structure obtained with the

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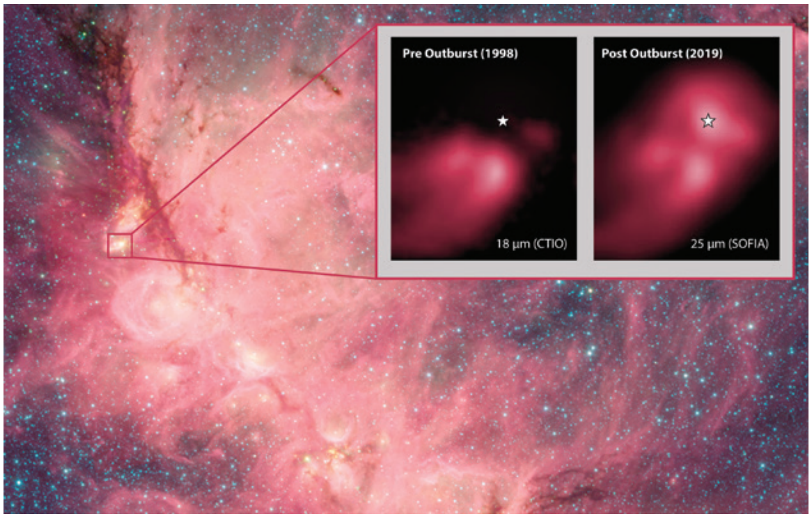
## Science Spotlight

James De Buizer, *Universities Space Research Association*
Joan Schmelz, *Universities Space Research Association*

# Episodic Accretion in High-Mass Protostars



The Cat's Paw Nebula (NGC 6334), imaged here by NASA's Spitzer Space Telescope using the IRAC instrument, is a star-forming region inside the Milky Way galaxy. The dark filament running through the middle of the nebula is a particularly dense region of gas and dust. The inset shows the region of the high-mass protostar with pre- and post-outburst luminosity. *(Cat's Paw Nebula: NASA/JPL-Caltech; Left inset: De Buizer et al. 2000; Right inset: Hunter et al. 2021)*

The realization that protostellar emission can be highly variable began in the 1960s with the recognition that the 6-magnitude optical brightening of FU Ori arose from a young stellar object rather than a nova. Similar scale outbursts have since been found in dozens of low-mass protostars, offering strong evidence that stars form via slow, continuous accretion punctuated by bursts of rapid, episodic accretion of matter from the circumstellar disk. The observed timescales of outbursts span a broad range from several months to a few hundred years.

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. While these events are observationally well established in low-mass stars like our Sun, comparatively little is known about the formative years of massive stars. Recent data from SOFIA, however, were crucial in characterizing the brightest and longest-lived accretion burst of a nascent high-mass star.

While monitoring NGC 6334 I, a well-studied proto-cluster, researchers discovered a millimeter outburst from a massive protostar with the Atacama Large Millimeter/submillimeter Array (ALMA). Unlike its proto-cluster companions, this protostar is so deeply embedded that it was only observable prior to the outburst at millimeter-to-radio continuum wavelengths, too obscured to be seen by Spitzer or any other near- or mid-infrared facility.

### About this Spotlight

**Paper:** The Extraordinary Outburst in the Massive Protostellar System NGC 6334 I-MM1: Strong Increase in Mid-Infrared Continuum Emission
**Authors:** T. R. Hunter, C. L. Brogan, J. M. De Buizer, A. P. M. Towner, C. D. Dowell, G. C. MacLeod, B. Stecklum, C. J. Cyganowski, S. J. El-Abd, B. A. McGuire
**Reference:** 2021 ApJL 912 L17.

Using SOFIA's Faint Object infraRed CAmera for the SOFIA Telescope (FORCAST) and HAWC+ instruments, the region was revisited after the discovery of the millimeter outburst. The observations revealed that infrared emission from the protostar had also increased considerably. Not only could the protostar now be seen in the infrared, but it was also now the brightest infrared source in the entire proto-cluster.

Combining the fluxes obtained from SOFIA mid- and far-infrared data with ALMA millimeter data, protostellar radiative transfer models were used to determine various stellar properties. Results indicated that the protostar has an outburst luminosity of almost 50,000 $L_{\odot}$, 16 times higher than the pre-outburst value. The SOFIA data were vital in determining an accurate measurement of this post-outburst luminosity.

A relatively new hypothesis contends that a large

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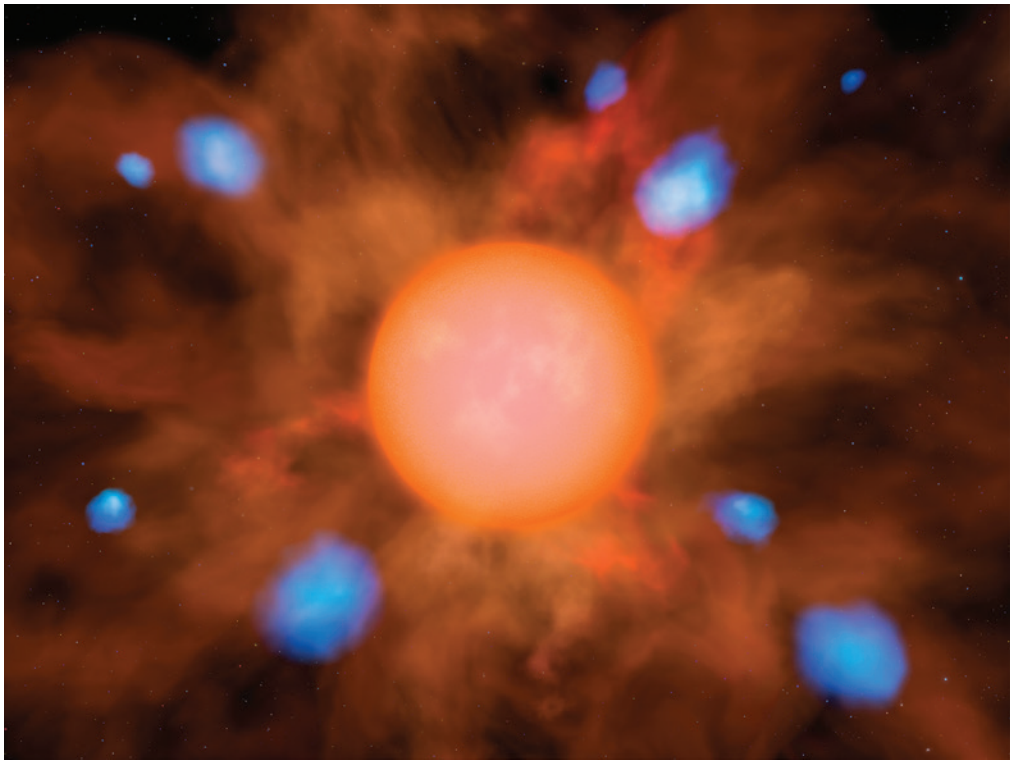
David Neufeld, *Johns Hopkins University*
Joan Schmelz, *Universities Space Research Association*

# New Observations of Terahertz Water Masers with SOFIA



Artist's impression of a pulsating variable star with an outflowing circumstellar envelope (orange) and embedded pockets of water masers (blue). The masing phenomenon occurs when a molecular transition exhibits a population inversion, and the rate of stimulated emission exceeds the rate of absorption resulting in a net negative absorption coefficient. Thus instead of being exponentially attenuated as it passes through an astrophysical medium, radiation is exponentially amplified. *(Lynette Cook)*

Fundamental astrophysical applications of maser amplification include tracing the structure and rotation of the Milky Way galaxy, probing the molecular accretion disks that feed black holes in active galaxies, and constraining the Hubble constant using masers as geometrical distance estimators. Key to these discoveries are the extraordinarily high intensities in specific molecular transitions — most notably the 1968 discovery of the 22 GHz transition of water vapor in the radio band — and subsequent observations with Very Long Baseline Interferometry that reveal gas motions at the highest spatial resolution.

While maser amplification must be carefully engineered in the laboratory, it can occur entirely naturally in low-density astrophysical environments. Over the half-century following the discovery of 22 GHz water masers, observations at ever higher frequencies have revealed the maser phenomenon in several additional $H_2O$ transitions. These include several lines in the 300–500 GHz range detected from ground-based observatories at dry, high-altitude sites; at 621 and 970 GHz detected with the Herschel Space Observatory; and at 1.296 THz detected by SOFIA in 2016 toward three oxygen-rich evolved stars, W Hydrae, U Herculis, and VY Canis Majoris, as well as one star forming region, NGC 7538-IRS1. Based upon a model for the circumstellar envelope of W Hydra, researchers estimated that stimulated emission was responsible for ~85% of the observed 1.296 THz line emission, thus confirming that this transition may be properly described as a terahertz-frequency maser.

Recent observations with the German REceiver for Astronomy at Terahertz Frequencies (GREAT) instrument

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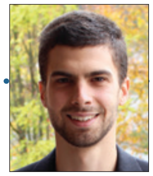
## About this Spotlight

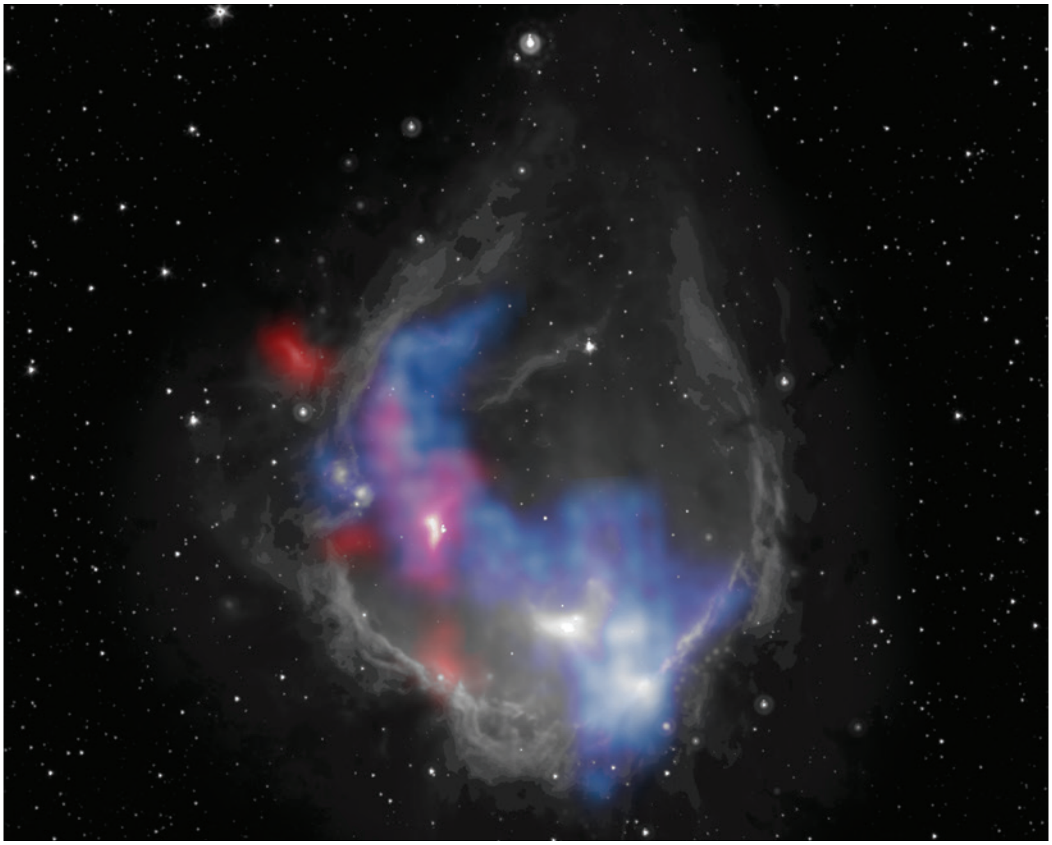
**Paper:** Terahertz Water Masers. II. Further SOFIA/GREAT Detections Toward Circumstellar Outflows, and a Multitransition Analysis
**Authors:** D. A. Neufeld, K. M. Menten, C. Durán, R. Güsten, M. J. Kaufman, A. Kraus, P. Mazumdar, G. J. Melnick, G. N. Ortiz-León, H. Wiesemeyer, F. Wyrowski
**Reference:** 2021 ApJ 907 42.

## Science Spotlight

Matteo Luisi, *West Virginia University*



# Stellar Feedback and Triggered Star Formation in RCW 120



Composite image of the nebula RCW 120. 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 gas represents gas expanding in the direction toward Earth and the red away from Earth. The expansion is triggering the birth of stellar neighbors at breakneck speeds — and revealing the nebula is younger than previously believed. *(NASA/JPL-Caltech/SOFIA)*

Recent SOFIA observations show that the high-mass star-forming region RCW 120 is expanding extremely fast. The rapid expansion causes molecular material at the outskirts of the region to pile up and be compressed, which leads to the formation of new stars around the region. While this process — known as positive stellar feedback — has been studied in a variety of environments, these new observations demonstrate for the first time that this type of feedback can operate on very short timescales, potentially shedding light on the star formation history of the universe.

High-mass stars affect their surroundings in a variety of ways. Their radiation ionizes and heats the surrounding gas, setting up ionized gas flows that remove material from the region. At the same time, their powerful stellar winds inject large amounts of kinetic energy into the environment. These processes are known to affect the future formation of stars by either compressing the surrounding material, which results in enhanced star formation, or by disrupting the material, which inhibits star formation. Although feedback processes are key to understanding star formation, their relative importance is unknown, making it impossible to fully understand the star formation history of our galaxy.

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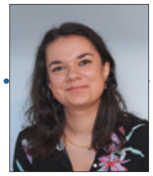
### About this Spotlight

**Paper:** Stellar feedback and triggered star formation in the prototypical bubble RCW 120

**Authors:** M. Luisi, L. D. Anderson, N. Schneider, R. Simon, S. Kabanovic, R. Güsten, A. Zavagno, P. S. Broos, C. Buchbender, C. Guevara, K. Jacobs, M. Justen, B. Klein, D. Linville, M. Röllig, D. Russeil, J. Stutzki, M. Tiwari, L. K. Townsley, A. G. G. M. Tielens

**Reference:** Science Advances 09 Apr 2021: Vol. 7, no. 15, eabe9511

Emma Beasor, *NSF's OIR Lab*



# The Age of Westerlund 1 Revisited

A key aim of massive stellar evolutionary theory is to understand which stars end their lives as supernovae and which ones do not. This is particularly relevant as the Vera Rubin Observatory prepares to come online, initiating an era of big-data, time-domain surveys where new supernovae will be discovered at a high rate every single night. For low-mass stars, their evolution can be understood by studying old, globular clusters. To do the same for massive stars, we must observe benchmark young massive clusters, for which we have determined the age, where we can see stellar evolution in action.

Westerlund 1 is a nearby Milky Way cluster, the only known analogue to the bright clusters seen in metal rich starburst galaxies where all of the individual stars can be resolved. Provided an age can be determined, this makes Westerlund 1 an ideal benchmark system for studies of more distant, high-redshift starburst galaxies. Stellar models of massive stellar evolution are essential for studying these high-redshift galaxies, but the only cluster they can be calibrated against is Westerlund 1.

Westerlund 1 also contains extreme stellar diversity, hosting a large variety of massive stars including blue, yellow, and red supergiants as well as Wolf-Rayets, a magnetar, and a luminous blue variable. Currently, we know of no other cluster in the universe that contains this level of extreme stellar diversity. Grids of stellar models that include single stars are only able to explain the stellar diversity (and hence total brightness, colors, and ionizing flux of the cluster) if the age of Westerlund 1 is 5 Myr. Any younger and the red and yellow supergiants would not have had enough time to evolve and cool; any older and all of the Wolf-Rayet stars would have already ended their lives as H-poor supernovae. Of course, this depends on the assumptions of a distinct age and the use of single-star models.

If the age of Westerlund 1 were 5 Myr, not only would it be the most massive stellar cluster in the Milky Way, but single-star evolutionary models would predict that the red and yellow supergiants were some of the most luminous ($>10^{5.5}\ L_\odot$) and massive ($>30M_\odot$) known. While the age of Westerlund 1 has been determined from the Wolf-Rayet and pre-main sequence stars, there have been no direct measurements of the luminosities of the cool supergiants.

Since red and yellow supergiants emit a large proportion of their flux at long wavelengths, optical as well as near-, mid-, and far-IR photometry is needed to determine the most accurate luminosities, but previous attempts have been hampered by saturated measurements from

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Image of young star cluster Westerlund 1 taken by the Hubble Space Telescope toward the southern constellation of the Altar. Westerlund 1 is home to some of the largest and most massive stars known, including four red supergiants, six yellow hypergiant stars, 24 Wolf-Rayet stars, and several more unusual stars that continue to be studied. Westerlund 1 is relatively close by for a star cluster at a distance of 15,000 light years, giving astronomers a good laboratory to study the development of massive stars. *(ESA/Hubble & NASA)*

## About this Spotlight

**Paper:** The Age of Westerlund 1 Revisited
**Authors:** E. R. Beasor, B. Davies, N. Smith, R. D. Gehrz, and D. F. Figer
**Reference:** 2021 ApJ 912 16

## Science Spotlight

Heinz-Wilhelm Hübers, *German Aerospace Center (DLR)*
Joan Schmelz, *Universities Space Research Association*

# Atomic Oxygen in Earth's Upper Atmosphere

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 — the mesosphere and lower thermosphere. These results from SOFIA help solidify some of the basic science around how solar energy is exchanged between the Earth's surface and space.

Since atomic oxygen plays an important role in cooling the upper atmosphere, it is used to estimate temperatures in this region. Climate models predict that increasing greenhouse gases will raise temperatures in the lower atmosphere yet decrease temperatures in the upper atmosphere, particularly in the mesosphere and lower thermosphere. But this region is difficult to study — ground-based telescopes are hampered by distortion from water vapor, satellites can infer levels of oxygen but cannot make direct measurements, while rockets and the space shuttle offered only brief snapshots of this region.

Atomic oxygen governs the photochemistry and the energy balance of the mesosphere and lower thermosphere. In addition, it can be used as a tracer for dynamical motions. Concentrations can be inferred indirectly from the oxygen air glow or from observations of hydroxyl. Such measurements have been performed with several satellite instruments, but the methods rely on photochemical models and assumptions such as quenching rates, radiative lifetimes, and reaction coefficients. As a consequence, the results are not always in agreement, particularly when obtained with different instruments.

Researchers have now explored an alternative approach, namely the observation of the $^3P_1 \rightarrow {}^3P_2$ fine-structure transition of atomic oxygen at 4.7 THz (63 μm) using the GREAT heterodyne spectrometer on SOFIA. With its high spectral resolution and sensitivity, GREAT enables unique measurements, both astronomical and atmospheric. This method has the advantage of measuring atomic oxygen directly, without involving photochemical models, because the populations of the states involved in this transition are determined solely by temperature and quantum mechanics. The line profile is Doppler broadened and varies between approximately 10 and 30 MHz depending on the altitude from where the emission originates. This means that the altitude information of the atomic oxygen concentration is contained in the line profile.

The atmospheric data are a by-product of astronomical observations in the same frequency band. The signal

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Noctilucent, or "night shining," clouds forming in the mesosphere as seen from the International Space Station on May 29, 2016. These clouds form between 47 to 53 miles (76 to 85 kilometers) above Earth's surface, near the boundary of the mesosphere and thermosphere, a region known as the mesopause. SOFIA is making direct measurements of atomic oxygen in this region, solidifying some of the basic science of how solar energy is exchanged between the Earth's surface and space. *(ESA/NASA/Tim Peake)*

### About this Spotlight

**Paper:** Direct measurements of atomic oxygen in the mesosphere and lower thermosphere using terahertz heterodyne spectroscopy
**Authors:** H. Richter, C. Buchbender, R. Güsten, R. Higgins, B. Klein, J. Stutzki, H. Wiesemeyer, and H. -W. Hübers
**Reference:** Commun Earth Environ 2, 19 (2021).

## Science Spotlight

Dario Fadda, *Universities Space Research Association*
Joan Schmelz, *Universities Space Research Association*

# Evidence of [CII] Shocked Emission in NGC 7479

SOFIA observations of the barred spiral galaxy, NGC 7479, were able to separate shock-enhanced ionized carbon [CII] emission from that associated with star formation, reminding us that it is important to consider multiple mechanisms when studying the [CII] emission in galaxies with active nuclei.

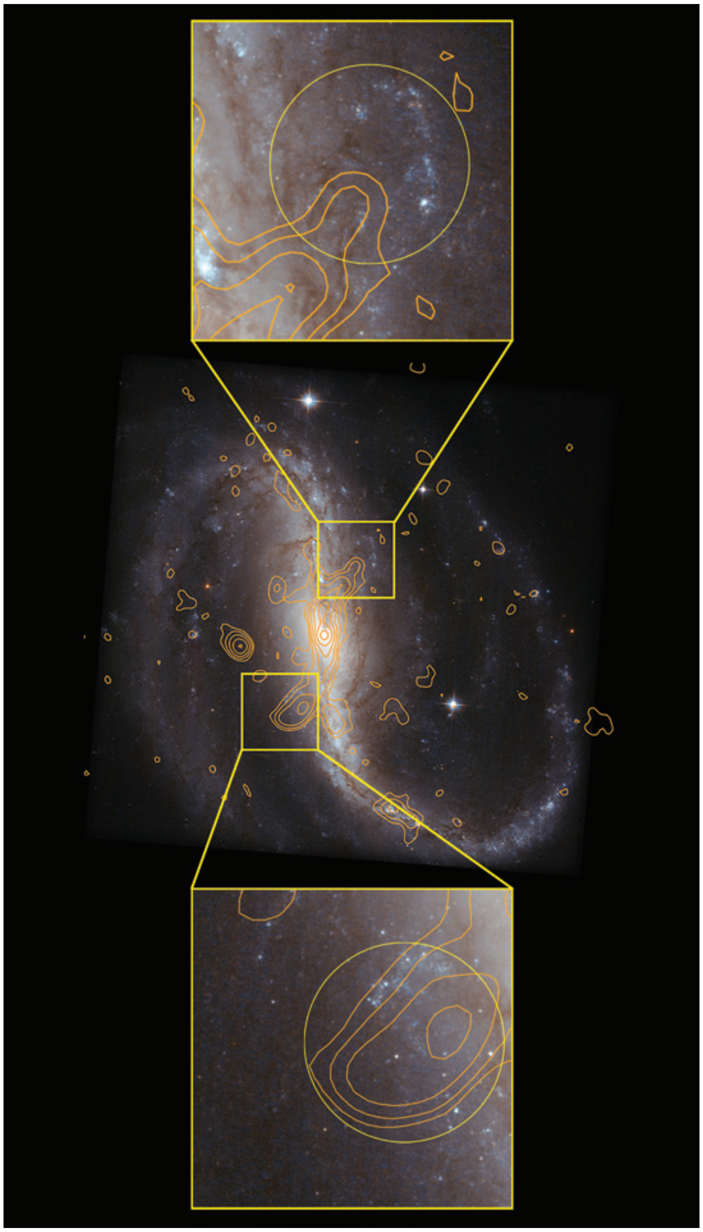
Infrared observations reveal that 70% of spiral galaxies exhibit barred structures. Since this percentage declines at higher redshifts, the bar is likely to form late in the life of a galaxy. Merging with smaller galaxies plays a major role in the evolution of bars, which efficiently channel gas to the nuclei and fuels the growth of central black holes. These processes lead to the formation of Active Galactic Nuclei (AGN). As the nucleus start energizing the surrounding medium via winds, jets, and radiation, it triggers star formation and suppresses further inflow by blowing the gas out, a process generally known as AGN feedback.

In the case of NGC 7479, the asymmetric shape of the arms is probably due to an episode of merging revealed by remnants along the bar and the dust lanes across the bar. However, the most peculiar feature of this galaxy is the presence of the so-called "counter-arms," which are clearly visible in the radio observations with a curvature opposite to the normal spiral structure seen in the optical image (see figure at right).

The morphology of the counter-arms is probably linked to jets from the hidden AGN at the center of the bar. Matter flows along the jets and collides with dense clumps of gas. Momentum is transferred to the gas along the axis of the bar, gradually changing the direction of the jet as the component of velocity along the bar decreases.

### About this Spotlight

**Paper:** [C ii] and CO Emission along the Bar and Counter-arms of NGC 7479*
**Authors:** D. Fadda, S. Laine, and P. N. Appleton
**Reference:** 2021 ApJ 909 204.



The Hubble Space Telescope image of NGC 7479 created from observations at visible and near-infrared wavelengths with 20 cm radio continuum contours in yellow (middle panel). The boxes highlight the ends of the lower and upper counter-arms; expanded versions of these regions are shown in the top and bottom panels where the circles depict the FIFI-LS aperture. *(ESA/Hubble & NASA)*

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# Magnetic Chaos Hidden Within the Whirlpool Galaxy

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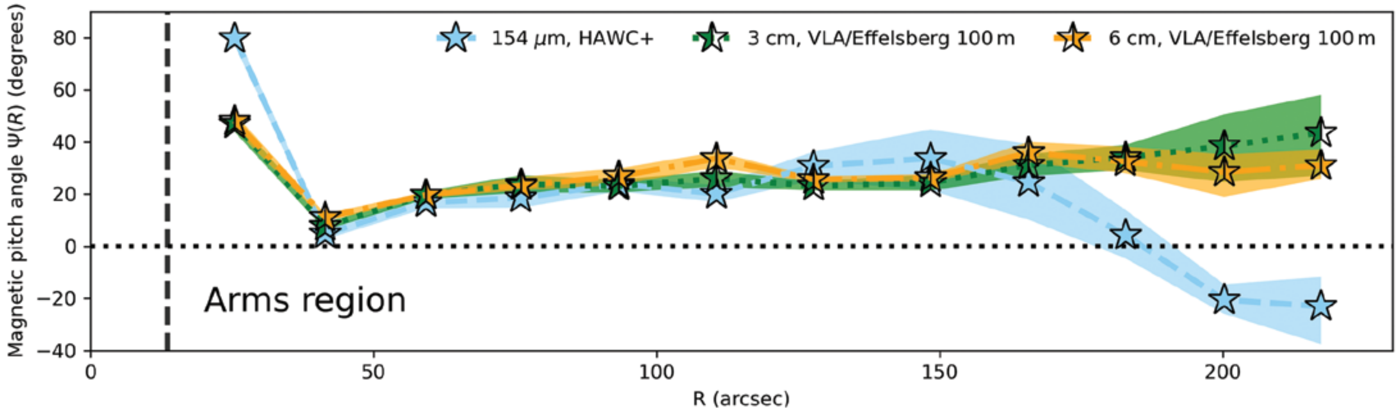
far-infrared observations shows a strong distortion and large differences in their orientation with respect to the structure obtained with the radio observations. This decoupling might be related to the gravitational interaction with Messier 51b, but strikingly, this effect is not found in the inter-arm region where the gas density is much lower and many fewer stars are forming.

Earlier models of the global structure and evolution of spiral galaxies that ignored the effects of magnetic fields were based on the hypothesis that the diffuse and molecular gas shared a common magnetic structure. The most important result from this work is the proof that there is a new force contribution to be reckoned with — the kpc-scale magnetic field of the molecular clouds.

The shape of spiral galaxies results from the pattern of bright H II surrounding newborn stars. The magnetic field lines are also spiral shaped, but intriguingly, astronomers are not yet sure how either of these structures — the morphological or the magnetic — are formed or how they are connected. The morphological spiral arms are possibly the result of density waves that move around the disk, compressing the gas, and creating new stars as they pass. At the same time, these density waves might also compress the magnetic field lines, aligning the turbulent fields that form inside the molecular clouds.

The observed differences between both tracers of the magnetic field support the presence of small-scale magnetic dynamos. When combined with galactic rotation and shear forces, these dynamos would help to create the striking spiral patterns visible in the magnetic field structure of the Whirlpool galaxy. Moreover, the observed differences between the orientation of the pitch angle in the inter-arm and arm regions also support the presence of spiral density waves, which would be compressing the magnetic field lines as the morphological spiral arms move through the galaxy.

The results from the SOFIA observations of the Whirlpool galaxy show that magnetic field lines are more turbulent in the densest regions of the gaseous galactic disk. Star formation processes, like supernovae or stellar winds, increase the gas turbulence in actively star-forming regions, distorting the magnetic field lines. This result was previously observed in our own galaxy, the Milky Way, but it is extremely difficult to detect in other galaxies due to their huge distances. Interestingly, the radio polarization observations suggest that it is in those turbulent regions where higher magnetic field strengths are found. This result, combined with the detected decoupling between the magnetic field structure of the diffuse and dense phases of the gas in the spiral arms, and the observed differences inside and outside the spiral arms, suggest that there is a tight connection between the gravitational interaction, star formation, spiral density waves, and the nature of galactic magnetic fields. ■



Magnetic pitch angle, Ψ(R), as a function of the galactocentric radius, R, for the spiral arms of the Whirlpool galaxy. Profiles show the far-infrared HAWC+ observations at 154 μm (blue) and the radio observations at 3 cm (green) and 6 cm (yellow). Note that the infrared and radio profiles are co-spatial in the inner part of the galaxy, but begin to deviate at around R=165 arcsec. Shading shows the uncertainty, and the black vertical dashed line shows the central beam of the observations. *(Borlaff et al. 2021)*

# New Observations of Terahertz Water Masers with SOFIA

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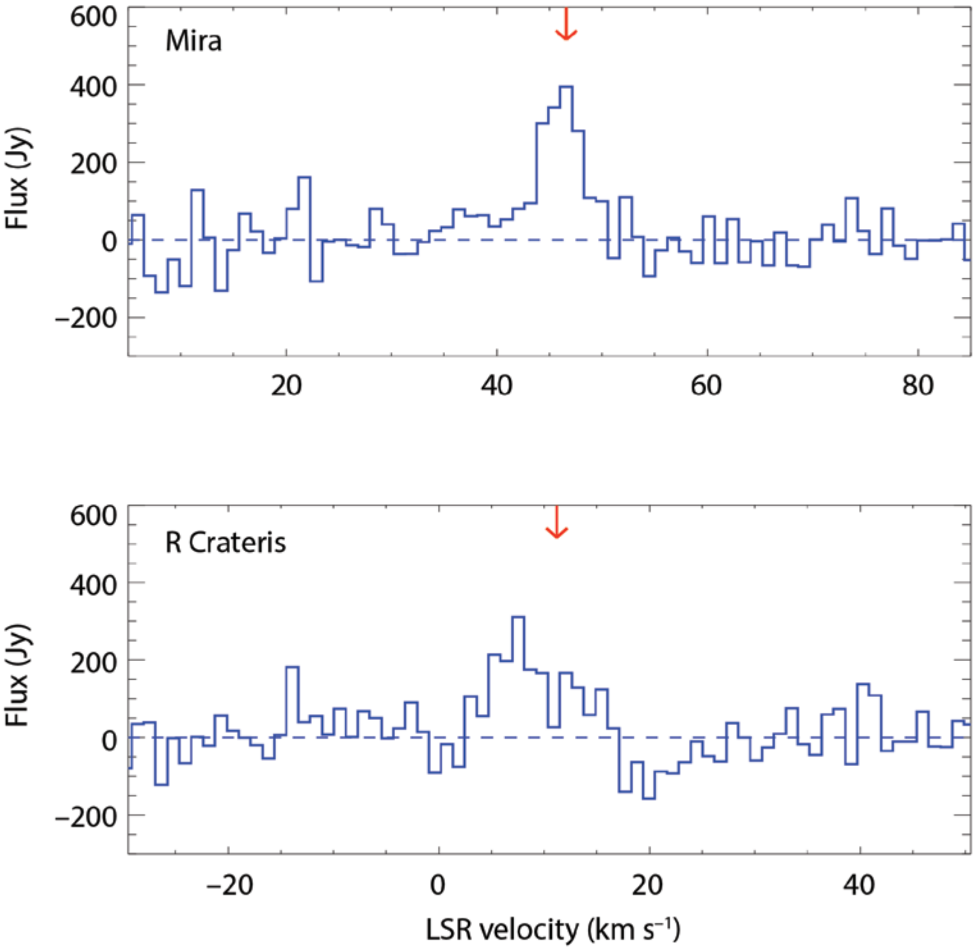
on SOFIA detected the 1.296 THz water maser transition in the outflowing circumstellar envelopes of two additional stars: Mira, a pulsating asymptotic giant branch star, and R Crateris, a semi-regular variable star. Researchers combined these measurements with ground-based observations of multiple lower frequency transitions of water. Such multitransition studies, which are critical for understanding the physical mechanism responsible for creating the population inversions that enable maser amplification, benefit from careful coordination because the maser fluxes can be highly variable. This entailed near-simultaneous observations at three observatories: SOFIA, the 100 m Effelsberg radio telescope in Germany used to observe the 22 GHz transition, and the APEX telescope in Chile used to observe other millimeter and submillimeter transitions.



Spectra of the 1.296 THz maser transition of water observed by the GREAT instrument on SOFIA toward the outflowing circumstellar envelopes of Mira and R Crateris. Red arrows indicate the systemic velocity of each star. Dashed lines indicate the baseline for each transition. *(Neufeld et al. 2021)*

The researchers combined these multiwavelength data and interpreted them using an excitation model. For each star, the model includes an estimate of how the gas temperature and density vary within the outflow, then computes the maser fluxes that are expected as a function of the assumed abundance of water vapor. In this model, the population inversions that enable maser amplification arise quite naturally from the combined effects of spontaneous radiative decay and collisional excitation in inelastic collisions between water molecules and molecular hydrogen (the dominant constituent of the gas); with the exception of one submillimeter maser transition, the model correctly predicts which transitions will be significantly inverted. Moreover, a quantitative comparison between the observed line fluxes and the model predictions allowed the water abundance to be estimated. For the five circumstellar outflows with terahertz-frequency maser detections, the implied water abundances fall in a rather narrow range, 1.4-2.5 × $10^{-4}$ water molecules per hydrogen molecule. These values are broadly consistent with the expectation that water vapor and carbon monoxide will be the primary reservoirs of oxygen within such outflows.

Thus, the latest SOFIA observations of terahertz water masers, in combination with ancillary data obtained from ground-based observatories, have yielded a consistent picture that explains the water maser phenomenon in circumstellar outflows. ■

# Stellar Feedback and Triggered Star Formation in RCW 120

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The nearby star-forming region RCW 120 is an ideal target to study the effects of feedback with SOFIA. RCW 120 is powered by a single high-mass star, and its morphology in the plane of the sky is almost perfectly circular. There is evidence of recent and ongoing star formation around the edges of RCW 120, particularly toward the south, which was most likely triggered by feedback from the massive star.

Researchers used the (up)GREAT receiver on SOFIA to measure fine-structure line emission from ionized carbon in RCW 120. The [CII] line is the main cooling line for diffuse gas and traces the photodissociation zone separating the fully ionized star-forming region from the neutral surrounding medium. With (up)GREAT, observers can now, for the first time, map large areas in [CII] and at sub-km/s velocity resolution, making it possible to disentangle the kinematics of nearby star-forming regions.

The [CII] observations of RCW 120 reveal that the region is rapidly expanding toward us. This blue-shifted signal has a high degree of symmetry, consistent with a half-shell expansion velocity of ~15 km/s. Given the physical size of RCW 120, this suggests that the region is only ~150,000 years old, much younger than previously thought. Supplementary X-ray observations reveal bright emission from hot gas within RCW 120. This emission is caused by the stellar wind of the massive star, which shocks the surrounding medium and drives the expansion of the shell. The shell then moves outward, where it compresses the surrounding molecular material, as seen by complementary APEX CO data. The molecular gas has already formed numerous clumps, many of which have already collapsed or are in the process of collapsing and forming new stars.

The energetics involved suggest that the stellar wind is indeed the main driver of the expansion of the shell, as other effects like photoionization cannot provide the necessary energy. The ratio of the kinetic energy of the swept up shell to the thermal energy of the hot plasma is possibly much larger than predicted by theory. The thermal energy, however, may be reduced due to a breach in the north-east quadrant of RCW 120, where hot plasma appears to be leaking out of the region. Toward the backside of RCW 120, the expansion speed of the shell is lower, suggesting that the molecular gas there is denser.

> ***The energetics involved suggest that the stellar wind is indeed the main driver of the expansion of the shell, as other effects like photoionization cannot provide the necessary energy.***

As there is ongoing triggered star formation around RCW 120, our observations imply that the feedback processes responsible for the formation of these stars must operate on very short timescales (<150,000 years), suggesting that positive feedback is a rapid process.

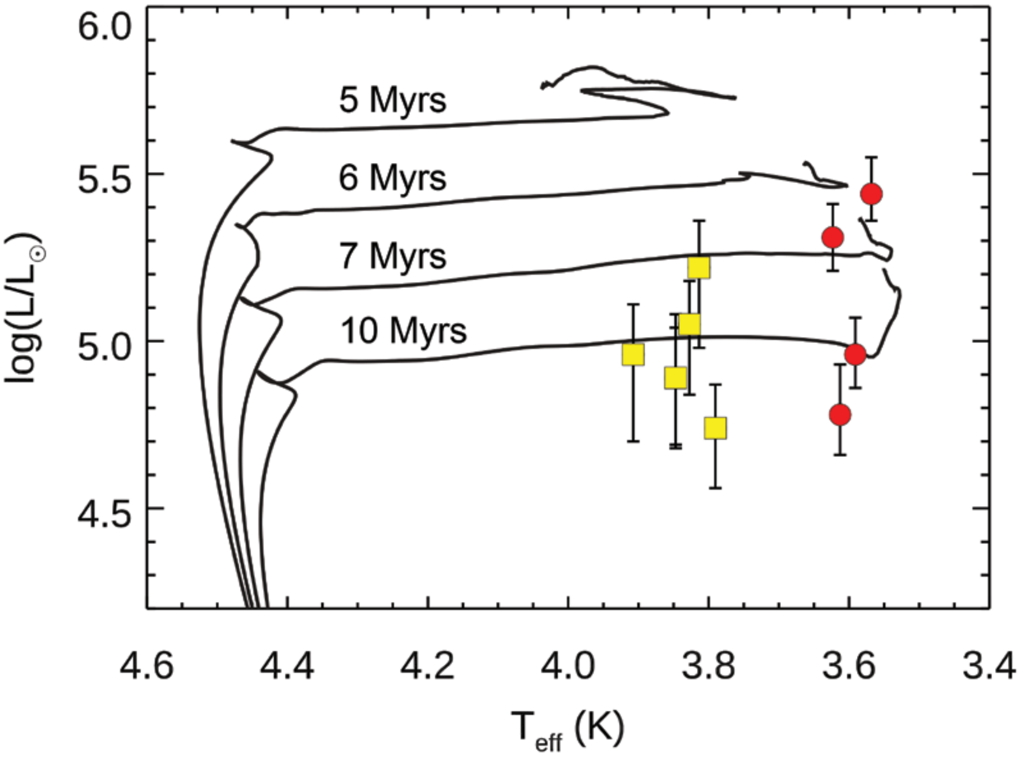
If this result is representative for star-forming regions, they may have major ramifications for the study of galaxy formation in the early universe and their subsequent evolution. Little is known about the formation mechanisms of stars in the early universe. Stars back then are expected to have been massive, and they therefore would have produced strong feedback effects. Rapid triggered star formation around these massive stars may have played an important role, possibly contributing to the large star formation densities observed in high-redshift galaxies. ■

# The Age of Westerlund 1 Revisited

*(continued from page 7)*

space-based observatories.

SOFIA FORCAST imaged Westerlund 1 in the wavelength range of 5.6–31.5 µm, covering a crucial portion of the spectral energy distribution where a large proportion of flux is emitted. Accessing wavelengths longer than 10 µm ensures any optical light lost to circumstellar extinction is captured when it is re-emitted at longer wavelengths.



Hertzsprung-Russel diagram for the cool supergiants in Westerlund 1. The red supergiants (red circles) and yellow supergiants (yellow boxes) are plotted along with stellar isochrones (black curves). The supergiant luminosities are clearly inconsistent with the previous age estimate of 5 Myr. Instead, they appear to be an older population consistent with an age of 10 Myr. *(Beasor et al. 2021)*

The new FORCAST photometry was combined with complimentary, archival photometry at shorter wavelengths to derive a bolometric luminosity for each cool supergiant. The results are on average 0.5 dex too faint to be consistent with an age of 5 Myr. Instead, comparing the cool supergiants to stellar isochrones implies they are more consistent with an age of 10 Myr, and ages of less than 6 Myr are excluded at the 99.9% confidence level.

Including systematic uncertainties on distance and foreground extinction in revised age estimates for Westerlund 1 indicate that the best fit results are also consistent with the 10-Myr age implied by the cool supergiants.

The only remaining source of contention comes from the high-mass eclipsing binary system, W13, for which dynamical masses are estimated at 22 and $33M_\odot$. Eclipsing binaries can place an age limit on a system by taking the lifetime of the highest mass component in the system.

The age implied by the mass of the $33M_\odot$ star, if that is the true initial mass, is younger than the cluster's new inferred age. However, given this is a close eclipsing binary system, the more massive $33M_\odot$ star could have potentially gained mass in stable mass transfer, meaning it was born with a lower initial mass. If this is the case, the true age could be older than that of a $33M_\odot$ star, so it remains unclear if this is in contention with the cool supergiant age.

Given the low luminosities of the cool supergiants and the high mass for the eclipsing binary system, it is clear that a single age of 5 Myr cannot explain the stellar population of Westerlund 1. Instead, it is likely Westerlund 1 is not a coeval starburst cluster, but the product of a prolonged period of star formation lasting roughly 5 Myr. Whatever the reason, given the presence of an older, lower mass cool supergiants population, Westerlund 1's position as the most massive cluster in the Milky Way must be evaluated. In addition, Westerlund 1 is not an appropriate benchmark object for studies of distant starburst galaxies or for calibrating stellar evolutionary models. Indeed, while Westerlund 1 may not be a Rosetta Stone object for stellar evolution, it certainly highlights how complex and surprising the universe can be. ■

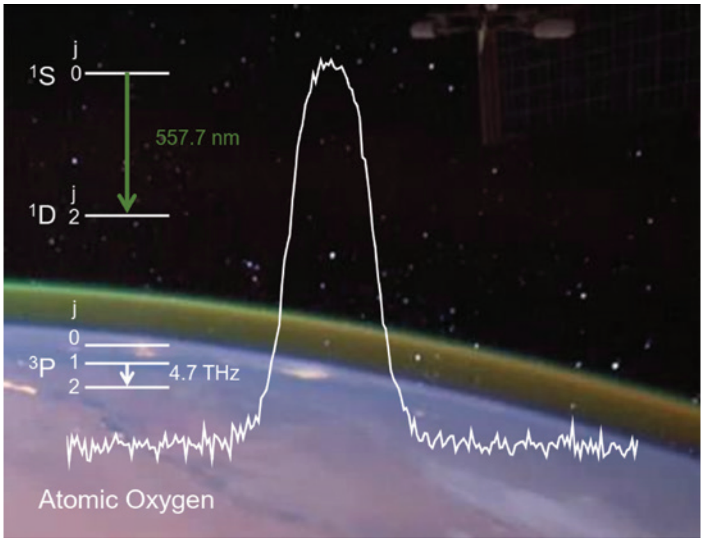
## Atomic Oxygen in Earth's Upper Atmosphere

*(continued from page 8)*

from the astronomical object is significantly Doppler shifted (up to ~3 GHz) from the atmospheric line, so they can be readily separated. Astronomers have always treated the atmospheric data as contamination and filtered it out from the sought-after celestial signal. While researchers saw that the atmospheric data could itself be valuable, it took several years to develop the right tools and processes to calibrate and analyze it.

For analysis of the spectra, researchers developed a radiative transfer code based on atomic oxygen concentration and temperature profiles from a semi-empirical model and satellite measurements. The expected atomic oxygen emission was modeled and compared with the emission measured by GREAT. The agreement was quite good, with differences within the uncertainty.

A trove of atomic oxygen data from many seasons and locations obtained with GREAT and upGREAT already exists in the SOFIA data archive. upGREAT adds the fine-structure transition at 2.06 THz. The SOFIA measurements are an important step towards a conclusive understanding of the Earth's upper atmosphere and reliable confirmations of climate model predictions. ■



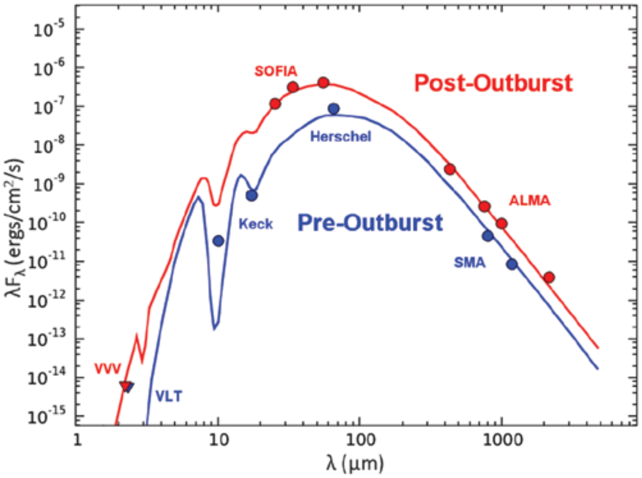
Air glow above the horizon of the Earth. The green color is caused by the 557.7-nm transition of atomic oxygen as shown by its energy spectrum in the inset (not to scale). The spectrum (total width: 170 MHz) indicated by the white curve is the ground state emission of atomic oxygen at 4.7 THz. The image of the air glow was taken by astronauts aboard the International Space Station. *(DLR/NASA)*

## Episodic Accretion in High-Mass Protostars

*(continued from page 4)*

uptick in the accretion rate of a massive protostar may be accompanied by the bloating of the photosphere. This not only results in a larger radius but also in a lower effective temperature. This would, in turn, lead to a lower stellar flux of ionizing radiation, a prediction that was confirmed by post-outburst 1.3-cm Very Large Telescope observations.

Among the most interesting aspects of this protostellar outburst are the remarkably large brightness and longevity. The NGC 6334 I outburst now exceeds all other outbursts by a factor of about three in both duration and energy output. These observations show the importance of continuous access to the mid-infrared to enable time-domain studies of the important accretion stage of massive star formation. ■



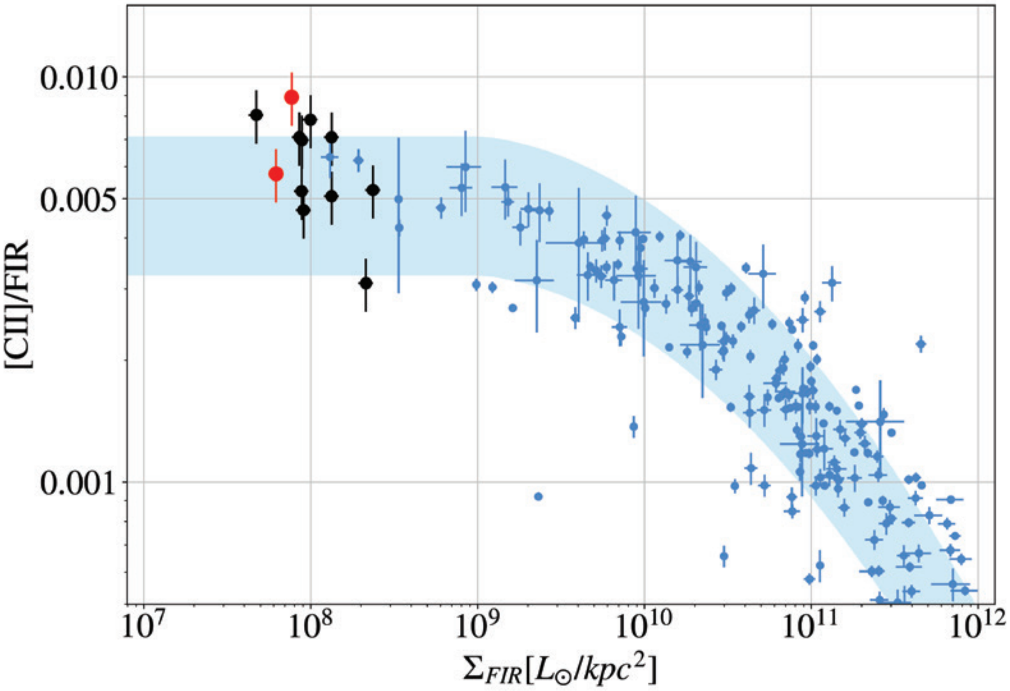
Pre-outburst (blue) and post-outburst (red) spectral energy distributions from radiative transfer models for the episodic accretion event in NGC 6334 I. Blue data points are from the Very Large Telescope, Keck, Herschel, and the Sub-Milimeter Array. Red data points are from VISTA Variables in the Via Lactea (VVV) Survey, SOFIA, and ALMA. *(Hunter et al. 2021)*

# Evidence of [CII] Shocked Emission in NGC 7479

*(continued from page 9)*

As the jet exits the bar and enters the less dense disk region, the direction of the jet will remain constant.

SOFIA observed the entire bar and counter-arm structure of NGC 7479 with the Far Infrared Field-Imaging Line Spectrometer (FIFI-LS) to study the distribution and intensity of the [CII] line at 157.7µm. This is the first complete [CII] observation of a galaxy bar ever done. The SOFIA study concludes that most of the [CII] emission comes from the molecular gas along the bar. However, the emission from the ends of the counter-arm structure is more complex.



Ratios of [C II] over far-IR emission as a function of the infrared surface brightness. The blue symbols depict observations from a comparison sample (Diaz–Santos et al. 2017) and the shaded band is the fitted curve with 1-σ uncertainty showing the zone where the [C II] emission is compatible with star formation. The black and red symbols represent the data for the northern and southern counter-arm regions, respectively. *(Fadda et al. 2021)*

The top and bottom panels of the image (see figure on page 9) show many blue young stars, but the relative positions of these stars are different with respect to the tip of the radio emission. The northern end (top panel) shows a bubble-like structure of bright young stars, but the southern end (bottom panel) is only partially surrounded. This suggests that the southern end of the jet was able to escape the disk of the galaxy and expand into the lower-density molecular gas of the halo where it is much less likely to trigger new star formation.

> ***The SOFIA study concludes that most of the [CII] emission comes from the molecular gas along the bar. However, the emission from the ends of the counter-arm structure is more complex.***

In addition, infrared diagnostics show that the [CII] emission is compatible with star formation in the northern region but much more intense than expected from star formation in the southern region (see above plot). This excess [CII] emission probably originates in warm shocked molecular gas heated by the interaction of the radio jet forming the counter-arms with the interstellar medium in the galaxy.

These SOFIA observations are helping to interpret studies of distant galaxies where the [CII] line is redshifted into the radio band and generally appear as point sources when observed with ALMA. Without the structural context provided by nearby galaxies like NGC 7479, the [CII] line strength might be used as a simplistic proxy for the star formation rate, unaware of how other energy sources may be contributing to the [CII] emission. ■

SOFIA undergoes annual maintenance during Fall 2021 at NASA's Armstrong Flight Research Center in California, including both routine aircraft maintenance and specialized procedures unique to the aircraft. One of the specialized procedures is maintenance of the upper rigid door that opens to allow the telescope to view the sky. In these images, the SOFIA team attaches the upper rigid door to a crane, then lifts and gently lowers the door onto a stand for inspection and servicing. *(Top left, bottom right: Syd Meyers; top right, bottom left: NASA/Agnew)*

SOFIA is a joint project of NASA and the German Space Agency at DLR, consisting of an extensively modified Boeing 747SP aircraft carrying a 2.7-meter (106 inch) reflecting telescope (with an effective diameter of 2.5 meters or 100 inches). DLR provides the telescope, scheduled aircraft maintenance, and other support for the mission. 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 at the University of Stuttgart. The aircraft is maintained and operated by NASA's Armstrong Flight Research Center Building 703, in Palmdale, California.

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