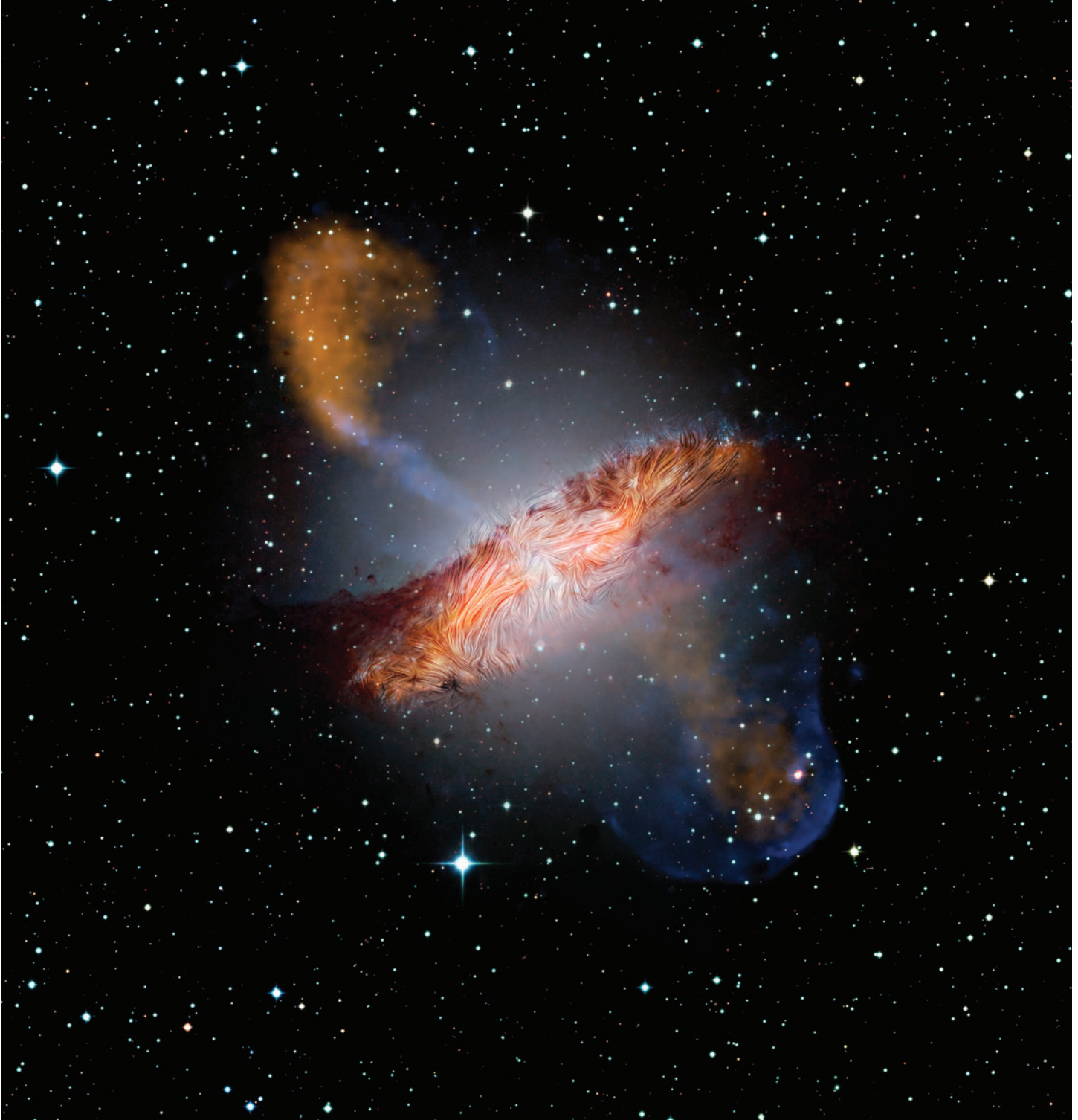


SOFIA Science



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A composite image of Centaurus A. See Science Spotlight, [page 3](#). (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)

SOFIA Observers Resources

SOFIA offers the following tools and documentation to facilitate the proposal process. These resources are available at: <https://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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Science Spotlight

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The Warped Magnetic Field of Centaurus A

Magnetic fields are thought to be generated at early stages of the universe from inhomogeneities and anisotropies of electric charges. Thus, the fields that we observe today are the result of the amplification of that “seed” field due to galaxy formation, accretion flows to supermassive black holes, and supernovae explosions. The understanding of the origin, amplification, and morphology of the magnetic fields is crucial for a complete picture of galaxy evolution.

Thanks to radio polarimetric observations, nearby galaxies are known to have large-scale spiral-like coherent magnetic field structures of kpc-scales. These magnetic fields are thought to be generated by galactic dynamos that convert kinetic to magnetic energy. This conversion can be performed via small-scale turbulent fields and differential rotation of the galactic disk to amplify and order the magnetic fields. Current theories can be divided into large-scale dynamos, which produce ordered magnetic fields on scales larger than the flow scale, and small-scale dynamos, generated at scales smaller than the energy-carrying eddies.

Recently, more attention has been given to small-scale dynamos as they require more generic flows and exhibit faster magnetic field growth. The amplification of small-scale fields is of the order of the smallest turbulent eddy turnover time scale. This is important because the small-scale fields allow amplification even in clusters and ellipticals. It can also explain strong magnetic fields in high-redshift galaxies when the universe was much younger and large-scale dynamo amplification times were not sufficient. Magnetohydrodynamic simulations suggest that weak initial “seed” fields were first amplified by a small-scale dynamo during a violent, feedback-dominated early phase in the galaxy formation history, which was



Composite image of Centaurus A. Magnetic fields from SOFIA are shown as streamlines over an image of the galaxy taken at visible and submillimeter wavelengths by the European Southern Observatory and Atacama Pathfinder Experiment, X-ray wavelengths from the Chandra X-Ray observatory and infrared from the Spitzer Space Telescope. (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)

followed by a more quiescent evolution where the magnetic fields have slowly decayed or were maintained via large-scale dynamo action.

Centaurus A is the remnant of a merger between an elliptical and a spiral galaxy that took place about 160 million years ago. The most prominent feature is the giant jets extending up to 250 kpc into the intergalactic medium. These jets are generated by accretion onto the supermassive black hole at the core of the galaxy. The

(continued on page 12)

About this Spotlight

Paper: The magnetic field across the molecular warped disk of Centaurus A

Authors: E. Lopez-Rodriguez

Reference: *Nature Astronomy* 2021.

Science Spotlight

Sarah Nickerson, *Bay Area Environmental Research Institute*
Naseem Rangwala, *NASA Ames Research Center*
Joan Schmelz, *Universities Space Research Association*



EXES Probes the Heart of Hot-Core Chemistry

High-resolution molecular line surveys provide a chemical inventory for star forming regions — essential for establishing the relative importance of potential chemical networks, understanding organic chemistry associated with star formation, and providing constraints on the supply pathways of key organic molecules in Earth-like planet formation.

Previous high spectral resolution line surveys have been limited to radio, sub-mm, and far-infrared wavelengths, but mid-infrared (MIR) observations are the only way to study symmetric molecules like CH_4 , C_2H_2 , and C_2H_6 that have no dipole moment and thus cannot be observed through rotational transitions. The MIR astronomical missions such as the Infrared Space Observatory (ISO) and Spitzer had low to moderate resolving power. Therefore, they were only able to identify molecular bands and could not resolve their individual rovibrational transitions needed to identify specific molecules with certainty. Due to the lack of high spectral resolution data in the MIR, the model chemical networks require testing and refinement in this regime.

The first comprehensive high-resolution molecular-line survey targeting the longer MIR from 12.5–28.3 μm with SOFIA's Echelon-Cross-Echelle Spectrograph (EXES) instrument opens up a new, largely unexplored discovery space.

Researchers targeted the hot core IRC2 in Orion, the nearest and best-studied region of massive star formation. Here, some early results from this survey are described, including the first MIR detections of HNC and H_{13}CN in the target region.

About this Spotlight

Paper: The First Mid-infrared Detection of HNC in the Interstellar Medium: Probing the Extreme Environment toward the Orion Hot Core
Authors: S. Nickerson, N. Rangwala, S. W. J. Colgan, C. DeWitt, X. Huang, K. Acharyya, M. Drozdovskaya, R. C. Fortenberry, E. Herbst, T. J. Lee
Reference: 2021/01, *ApJ*, 907, 51.

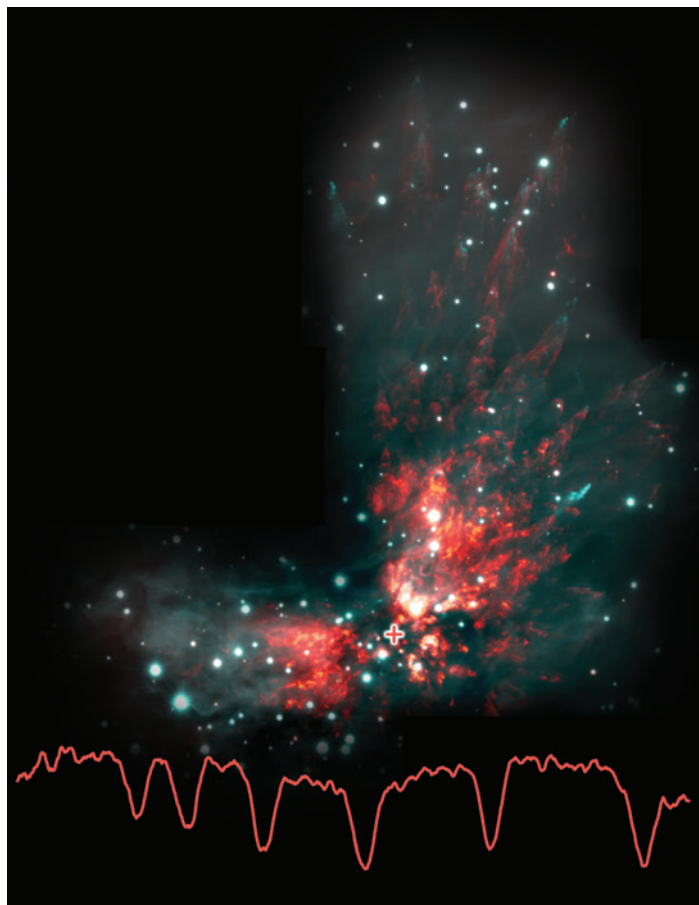


Image of the Orion KL region taken by the Gemini South Telescope. The cross marks the approximate position of the Orion hot core located at the center of an explosion generated by a multibody dynamical encounter about 500 years ago. The H_2 in red and [FeII] in blue trace finger-like tendrils resulting from the blast. The SOFIA EXES spectrum across the bottom of the image shows the Q1e–Q6e ro-vibrational transitions of the HNC molecule near 21.6 μm seen in absorption against IRC2. (*Orion*: Bally et al. 2015; Gemini South GSAOI; Spectrum: Nickerson et al., 2021)

HCN and HNC are astronomically ubiquitous. They are observed in our solar system, star-forming regions, and extragalactic sources. Though created in similar quantities at cool temperatures, the HNC molecule is less stable. The HCN/HNC abundance ratio is close to unity at the low

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Science Spotlight

Joan Schmelz, *Universities Space Research Association*
James Jackson, *Universities Space Research Association*

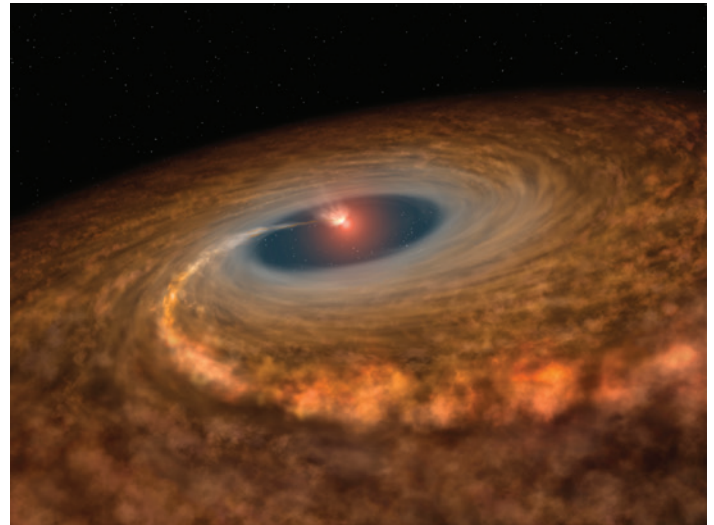


Episodic Accretion in Massive Star Formation

Theory has long suggested that the mass growth of protostars occurs stochastically in a series of episodic accretion events from the surrounding disk. Until the central protostar dominates the total mass of the system, the surrounding cool disk is highly susceptible to gravitational instabilities, resulting in stochastic accretion of clumpy disk components onto the protostar. During an accretion event, the luminosity of the protostar increases rapidly due to the conversion of gravitational energy to thermal radiation. Quantitative observational research on stochastic accretion has just begun, especially for high-mass stars.

A detailed study of massive young stellar objects is hindered by the large quantity of surrounding gas and dust, but infrared observations can penetrate these dense envelopes. Because the radiation generated from an accretion event emerges mainly in the mid- and far-infrared, SOFIA data are crucial for deriving the total luminosity of the young star and the fundamental parameters of the accretion burst. Since these massive young stellar objects are rare and their growth phases last only a small fraction of their lives, scientists need either very good luck or a successful search strategy to observe these events.

Methanol masers are signposts of massive young stellar objects. Recent evidence shows that flares of these masers are driven by accretion bursts. Thus, maser monitoring can be used to identify such bursts, which are



Artist's impression of a stochastic accretion event as a massive fragment of the clumpy accretion disk spirals onto the protostar. Fundamental parameters of the resulting burst such as the fragment mass and the energy released can be estimated by changes to the spectral energy distribution in the infrared measured by SOFIA. (Lynette Cook)

otherwise hard to discover. Infrared observations reveal burst-induced changes in their spectral energy distribution, which provide valuable information on this intense phase of high-mass star formation.

In mid-January 2019, maser flaring was reported of the massive young star called G358. The international maser community initiated an extensive observational campaign that revealed extraordinary maser activity and yielded the detection of numerous new maser transitions.

Since these bursts of brightness from growing young stars are mainly visible in the far-infrared, observations were obtained from the Far Infrared Field-Imaging Line Spectrometer (FIFI-LS) instrument on SOFIA. Integral-field spectroscopy was carried out to detect possible counterparts of the maser sources and compare their photometry to archival measurements. The comparison of pre-burst and burst spectral energy distributions confirmed the

(continued on page 15)

About this Spotlight

Paper: Infrared observations of the flaring maser source G358.93–0.03

Authors: B. Stecklum, V. Wolf, H. Linz, A. Caratti o Garatti, S. Schmidl, S. Klose, J. Eislöffel, Ch. Fischer, C. Brogan, R. A. Burns, O. Bayandina, C. Cyganowski, M. Gurwell, T. Hunter, N. Hirano, K.-T. Kim, G. MacLeod, K. M. Menten, M. Olech, G. Orosz, A. Sobolev, T. K. Sridharan, G. Surcis, K. Sugiyama, J. van der Walt, A. Volvach and Y. Yonekura

Reference: *A&A*, 646 (2021) A161

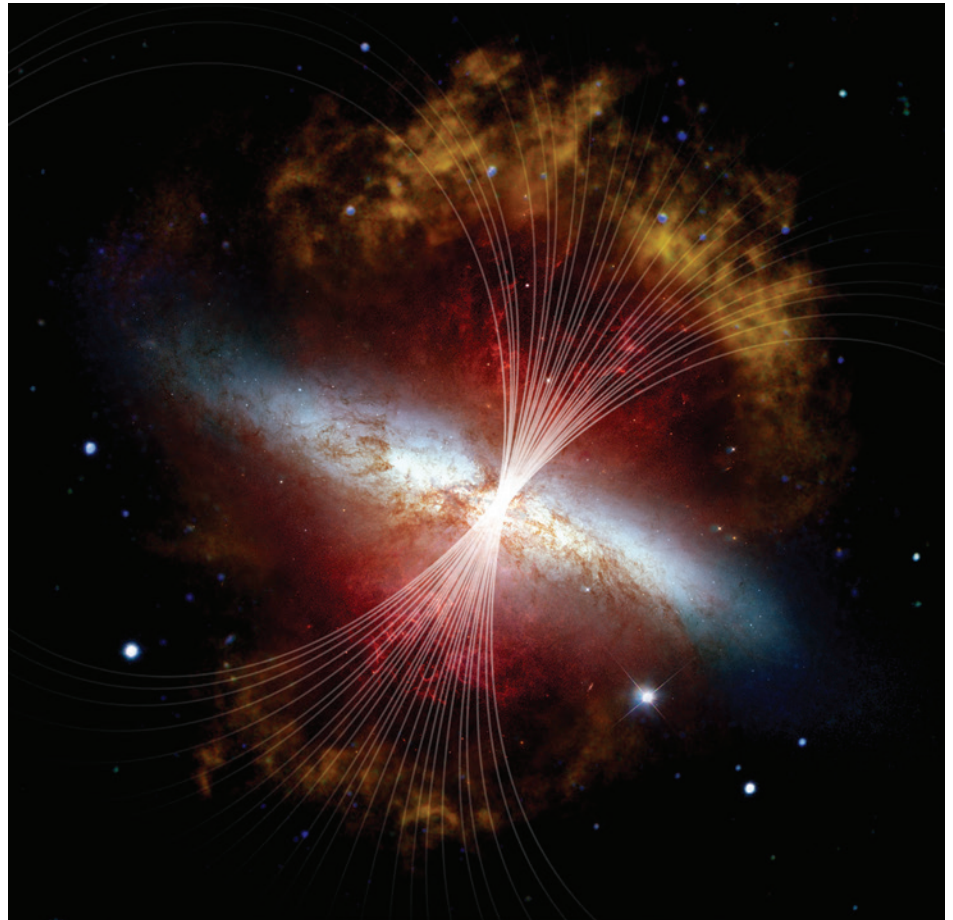


Magnetic Highway: Channeling the M82 Superwind

Observations of M82, a canonical starburst galaxy, reveal a bipolar superwind that originates in the core and extends out into the halo and beyond. Early observations from HAWC+ show that the geometry of the field at the base of the superwind is perpendicular to the plane of the galaxy, consistent with a scenario where the outflow is dragging the field along with it.

Do these magnetic field lines extend forever, channeling matter into intergalactic space, or do they turn over, directing material back to the galaxy in a giant feedback loop? This question is reminiscent of an analogy from solar physics — are the field lines emanating from the Sun open, like those in the solar wind, guiding particles from the solar surface to interplanetary space, or are they closed, like coronal loops, forming the complex structure of the solar atmosphere? We turned to a well-tested technique used in heliophysics — the potential field extrapolation — to answer this question.

With only rare exceptions, the magnetic field in the solar corona cannot be measured directly. Therefore, significant effort has been invested by the community into extrapolating the field



Magnetic fields lines in Messier 82 overlaid on a visible-and-infrared composite from the Hubble Space Telescope and the Spitzer Space Telescope. The galactic superwind from the central starburst is blasting out plumes of hot gas (red) and a halo of smoky dust (yellow/orange) perpendicular to the edge-on galaxy (white). Researchers used IR polarization data from SOFIA and tools that have been utilized extensively to study the physics around the Sun to extrapolate the potential magnetic field strength and structure up to 10 kpc around the galaxy. The field lines appear to extend indefinitely into intergalactic space, like the Sun's solar wind, creating magnetic highways that channel star-processed matter beyond the starburst core. (NASA, SOFIA, L. Proudfit; NASA, ESA, Hubble Heritage Team; NASA, JPL-Caltech, C. Engelbracht)

About this Spotlight

Paper: The strength and structure of the magnetic field in the galactic outflow of M82

Authors: E. Lopez-Rodriguez, J. Guerra, M. Asgari-Targhi, J. T. Schmelz

Reference: 2021, *ApJ*, in press

measured at the surface via the Zeeman Effect up into the solar atmosphere. The simplest of these approximations assumes that the electrical currents are negligible so the magnetic field has a scalar potential that satisfies the Laplace equation and two boundary conditions: it

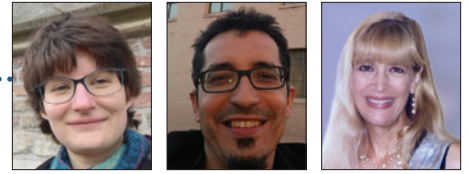
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Science Spotlight

Cornelia Pabst, *Leiden University*

Javier Goicoechea, *CSIC*

Joan Schmelz, *Universities Space Research Association*

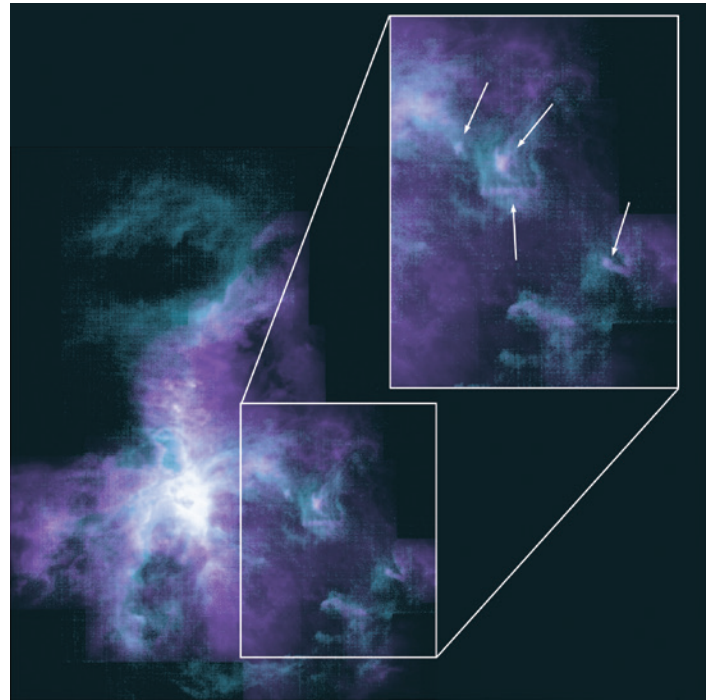


First Signs of Star Birth Triggered by Orion Wind

In the iconic Orion Nebula, an enormous stellar wind is blowing away its natal molecular cloud, forming a ridge of dense material along the edge of the resulting bubble. New results reveal signs of star birth along the edges within tiny, compacted clouds and offer new insights into how the stars of today can affect the stars of the future.

The young massive stars in the central Trapezium Cluster of Orion have created a bubble of hot X-ray emitting plasma that is enveloped by a shell of neutral gas and dust. The gas is heated by stellar radiation and cools mainly through the fine-structure line of ionized carbon, [CII], at 158 μm . The molecular gas situated in the star-forming cloud behind the nebula emits mainly in low-lying CO rotational transitions, such as the CO(2-1) line at 1.3 mm. When observed at very high spectral resolution, the Doppler shift in those lines can be used to trace gas motions.

SOFIA mapped an area of about one square degree — four times larger than the full moon — in the [CII] line emission from the Orion Nebula. The observations revealed that the neutral shell of disrupted material is expanding at 13 km/s away from the background molecular cloud. The wind from the central massive star, θ^1 Orionis C, is dominating stellar feedback, the processes that regulate future star formation. Stars can disrupt the dense gas of their birth environment, thereby preventing stellar siblings from forming nearby. Shock waves induced by stellar winds and radiation can lead to the compression of gas to trigger formation of new stars. Initially it was unclear if the powerful wind would facilitate or hinder star formation as the compacted material was pushed



Composite image of the Orion Nebula from SOFIA and the IRAM 30-meter radio telescope. The designated areas in the insert are densely compacted clouds with prime conditions for new stars, and in fact one newborn, low-mass star already seems to be forming there. (NASA/SOFIA/IRAM)

to the bubble's edges.

The SOFIA observations were complemented by CO(2-1) velocity-resolved maps taken with the IRAM 30-meter radio telescope in Spain. The absence of large-scale CO(2-1) emission from the shell implies that this [CII]-emitting gas is “CO-dark,” but not necessarily 100% atomic since molecules may still survive or reform in this harsh environment. Indeed, the CO(2-1) results reveal several small — about 10,000 astronomical units in size — globules of dense molecular gas along the edges of the neutral expanding shell. This unexpected result may provide the first clue of triggered star formation in Orion.

While most of the material in the massive neutral shell

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About this Spotlight

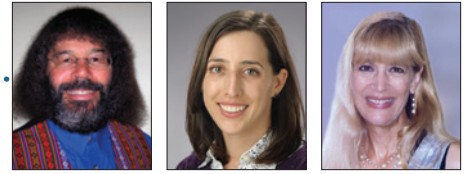
Paper: Expanding bubbles in Orion A: [CII] observations of M 42, M 43, and NGC 1977

Authors: C. H. M. Pabst, J. R. Goicoechea, D. Teyssier, O. Berné, R. D. Higgins, E. T. Chambers, S. Kabanovic, R. Güsten, J. Stutzki, A. G. G. M. Tielens

Reference: A&A 639, A2 (2020).

Science Spotlight

Charles “Chick” Woodward, *University of Minnesota*
Kassandra Bell, *Universities Space Research Association*
Joan Schmelz, *Universities Space Research Association*



SOFIA Comet Studies Explore the Carbon Gradient in the Solar System

SOFIA observations reveal that comets may be the source of carbon, an essential ingredient for life, for planets like Earth and Mars. Analysis shows that dynamically new comet, Comet C/2013 US₁₀ (Catalina), is carbon-rich, suggesting that it formed in the outer regions of the primordial solar system before delivering carbon to the terrestrial planets. These results reveal cometary dust carbon-to-silicon (C/Si) atomic ratios much higher than those of carbonaceous-chondrite meteorites, suggesting the outer protoplanetary disk, the realm where comets first formed, was richer in carbon than the inner disk. This finding contributes to newly proposed interpretations of disk processing in the primitive solar system.

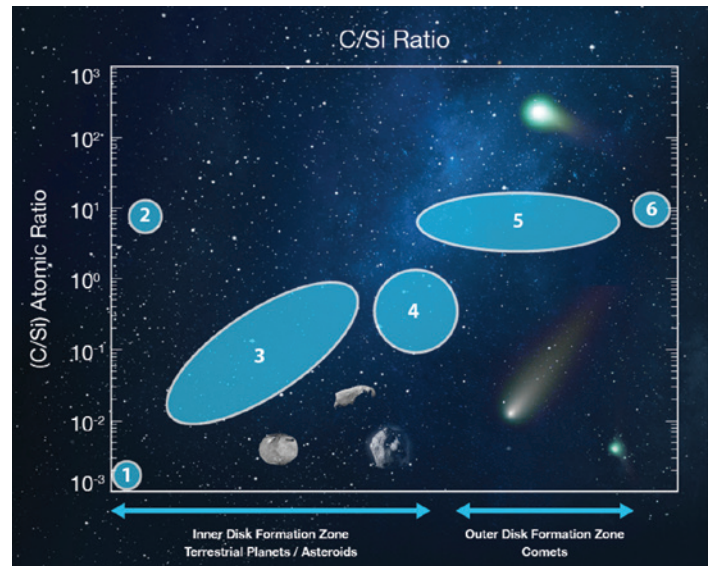
Comets are remnants of solar system formation. They have remained cryogenically “preserved” in the Oort Cloud for the last 4.5 billion years, minimally processed and retaining a record of the volatile and refractory material incorporated into their nuclei from the protoplanetary disk. Remote sensing of their comae probes the chemistry present in the natal solar system. Comet nuclei likely incorporated both processed nebular matter as well as material from the ISM. Deciphering how terrestrial planets might form in habitable zones with stable biospheres requires understanding the pathways of biogenic elements abundant in the ISM gas phase as materials are processed and redistributed within the disk. These materials were aggregated into rocks and ices, eventually accreted by terrestrial bodies. In particular, the disposition of carbon, the keystone in the chemistry of life, is of keen interest.

About this Spotlight

Paper: The Coma Dust of Comet C/2013 US₁₀ (Catalina): A Window into Carbon in the Solar System

Authors: C. E. Woodward, D. H. Wooden, D. E. Harker, M. S. P. Kelley, R. W. Russell, D. L. Kim

Reference: 2021 Planet. Sci. J. 2 25.



Atomic carbon-to-silicon ratio (C/Si) loci for (1) the bulk solid Earth; (2) the Sun; (3) meteoritic materials, including both non-carbonaceous and carbonaceous chondritic classes; (4) interplanetary dust particles; (5) SOFIA studied comets; and (6) the interstellar medium. (NASA/Greg Hogan/L. Proudfit/C. Woodward)

The inner regions of the solar nebula, closest to the primordial Sun, were so hot that only rocky material could survive. The terrestrial planets formed in this environment where elements like carbon were destroyed or removed via disk winds. SOFIA observations can address this so-called “carbon deficit,” where rocky bodies in the inner solar system including the Earth are generally depleted in carbon compared to outer regions of the solar nebula where it was cool enough for carbon to survive.

SOFIA observations show comets have C/Si atomic ratios similar to the ISM and the Sun. These results indicate the solid state materials present in the outer disk that were incorporated into comets efficiently sequestered carbon from the abundant carbon reservoir inherited from the ISM. The Faint Object infraRed CAmera for the

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Science Spotlight

William Reach, *Universities Space Research Association*
Joan Schmelz, *Universities Space Research Association*

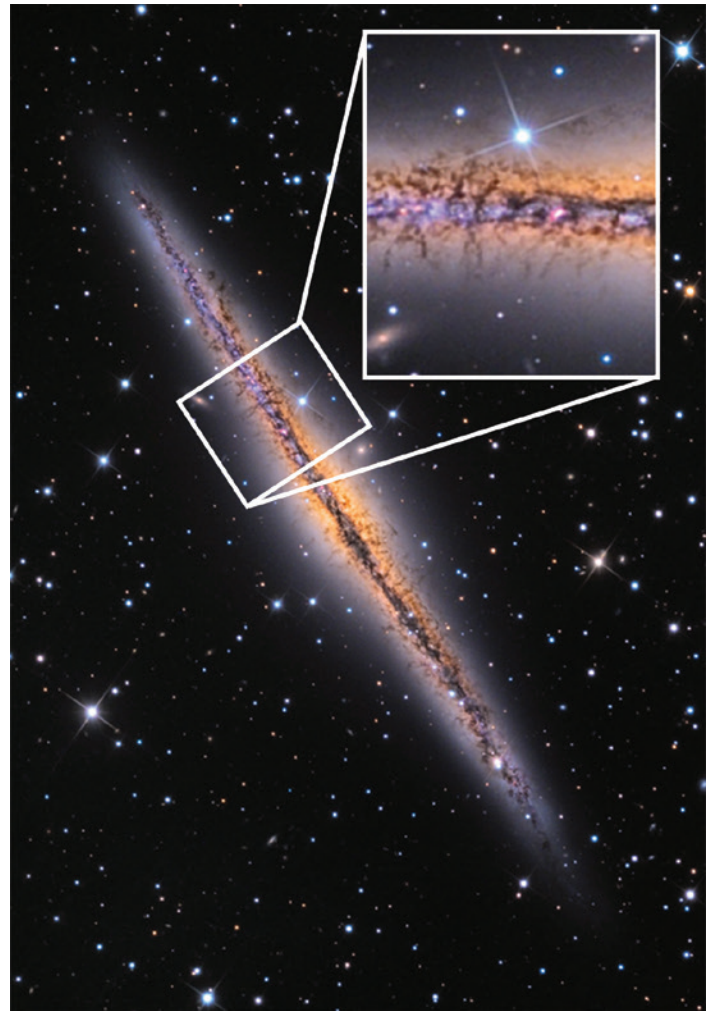


Galactic Chimneys: An Unseen Component of the Disk-Halo Interaction

Spiral galaxies are relatively thin, but when viewed edge-on, observers can discern emission extending above and below their midplanes. In general, this vertical distribution of material is determined by a balance between gravity from the stellar disk and pressure in the interstellar gas. But bursts of localized star formation can disturb this equilibrium. The largest stars in a cluster generate powerful winds and then explode as supernovae at the ends of their lives. Thus each cluster inputs vast amounts of energy into its surroundings, which can approach or even exceed the gravitational binding energy of material to the disk. This can drive material from the disk into the halo, leading to the formation of bubbles or vertical protrusions called chimneys.

A similar phenomenon occurs on a larger scale at the centers of some galaxies, where the exceptional rates of star formation or the supermassive black hole can produce superwinds like the one seen in M82 or large-scale Fermi bubbles like the one seen in our own Milky Way. All of these processes, either at the galactic center or in the outskirts, determine how galaxies evolve. Super star clusters can generate so much energy that they blow out their disks, destroying or disrupting the raw material required to form new stars. If this material escapes into the galactic halo, it may eventually return via a “galactic fountain” or seed the intergalactic medium with newly star-processed material.

Researchers used the FIFI-LS instrument on SOFIA to study the extra-planar distribution of [C II] in the two edge-on spiral galaxies, NGC 891 and NGC 5775. The [C II]



Optical image of the edge-on galaxy, NGC 891, showing dark, thread-like extinction features — walls of the chimneys — extending above and below the midplane. SOFIA [C II] observations reveal a significant mass of gas in the chimney walls. (Adam Block/Mount Lemmon SkyCenter/University of Arizona)

line at $157.7 \mu\text{m}$ is the primary cooling line for diffuse atomic and molecular gas. It is a good tracer of the ISM, complementary to the HI 21-cm and H α lines, which are sensitive to lower density gas. Emission was detected up

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About this Spotlight

Paper: Extraplanar Gas in Edge-on Galaxies Traced by SOFIA Observations of [C II]

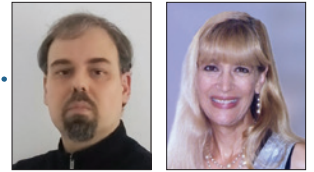
Authors: W. T. Reach, D. Fadda, R. J. Rand, G. J. Stacey

Reference: 2020 ApJ 902 28.

Science Spotlight

José Pablo Fonfría, *IFF-CSIC*

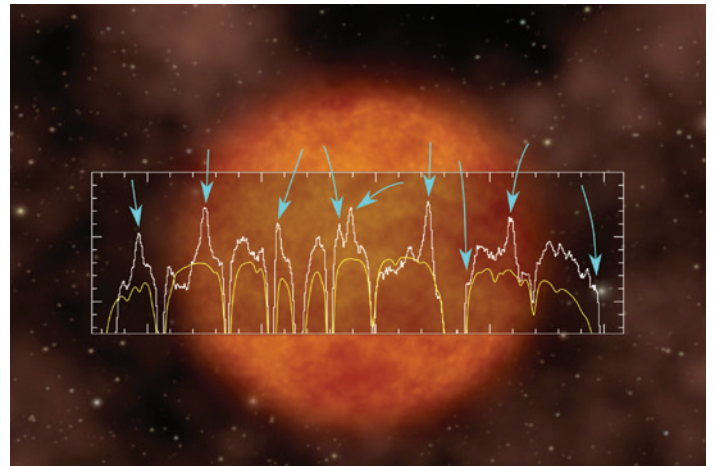
Joan Schmelz, *Universities Space Research Association*



Carbon Dioxide in R Leonis

The circumstellar envelopes of asymptotic giant branch (AGB) stars provide some of the richest chemical laboratories in space. Over 90 different molecules have been detected, most in the millimeter range where species with a permanent dipole often have strong transitions. Unfortunately, however, symmetric molecules like H_2 lack such transitions. Another such molecule, CO_2 , is predicted to be an abundant parent species for more complex organics. While CO_2 has been detected in AGB stars from space with low-spectral-resolution instruments on ISO and Spitzer, the extremely high atmospheric opacity makes it impossible to observe from the ground. For targets with suitable radial velocities, however, airborne observatories like SOFIA can use the Earth's orbital velocity to Doppler-shift the astronomical lines away from the atmospheric obstruction, which is significantly reduced at a cruising altitude of 40,000 ft.

AGB stars are cool giants of 0.8–8 solar masses that have left the Main Sequence. After exhausting most of the hydrogen in their cores and triggering further nuclear reactions based on helium, these objects have seen a dramatic increase of their stellar radii that could be as high as 2–3 AU, a decrease of their effective temperatures down to about 2,000–3,000 K, and the formation of a significant amount of heavier atoms (e.g., C, O, N, Si, S). Moreover, these stars are variable with pulsation periods of months to years. The increased radius results in a weakening of the gravity at the stellar surface, allowing material to be expelled by the pulsation movement and radiation pressure. The expelled matter, initially in atomic form, cools to form a rich variety of molecules and dust



A portion of the spectrum of R Leonis (white) superimposed on an artistic interpretation of the star. The arrows indicate several CO_2 emission line peaks near $13.5 \mu\text{m}$, and the yellow line is a model of Earth's atmospheric transmission. (NASA/JPL-Caltech; Fonfría et al. 2020)

grains. The analysis of the emission and absorption of these molecules offers valuable information to determine, for instance, the amount of ejected matter, the abundance of chemical elements produced by the star, and the chemical interactions between the ejected atoms in the circumstellar envelopes.

Carbon dioxide is predicted to be one of the most abundant molecules in the circumstellar envelopes of the oxygen-rich AGB stars, but because of the extreme observing difficulty mentioned above, the connection between the CO_2 abundance and the main characteristics of AGB stars is not well constrained. Furthermore, rotational temperatures of the circumstellar envelopes where the lines are formed can only be roughly determined from low spectral resolution data. Hence, it is difficult to compare these observations with results of currently available chemical models.

However, thanks to SOFIA, it was possible to get above most of the atmosphere and detect many lines of CO_2 in emission coming from the circumstellar envelope of the

(continued on page 11)

About this Spotlight

Paper: Detection of infrared fluorescence of carbon dioxide in R Leonis with SOFIA/EXES

Authors: J. P. Fonfría, E. J. Montiel, J. Cernicharo, C. N. DeWitt, M. J. Richter

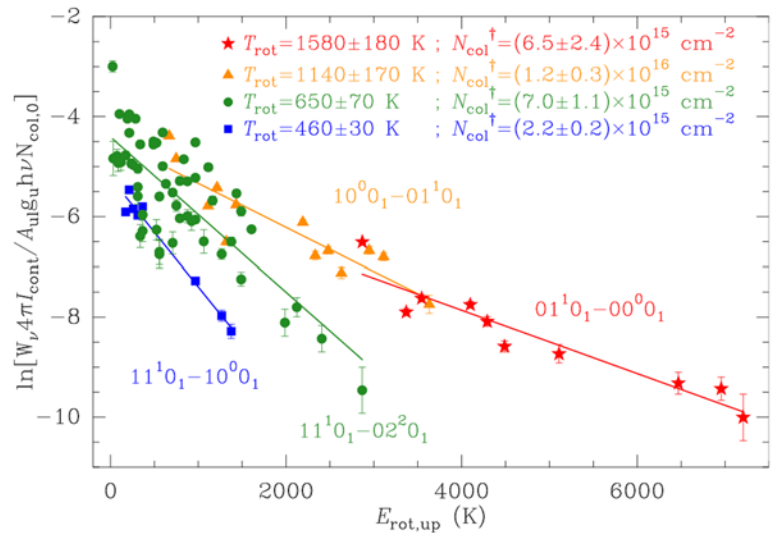
Reference: A&A 643, L15 (2020).

Carbon Dioxide in R Leonis

(continued from page 10)

target star, R Leonis. The observed lines indicate that a very high fraction of CO₂ molecules are close to the photosphere and affected by the strong stellar continuum. Their emission is produced by infrared fluorescence, where molecules are excited to high energy levels by the stellar continuum in the near-infrared and de-excite afterwards in the form of radiative cascades.

The observations reveal a rich spectrum of about 240 identified CO₂ lines. Using excitation diagrams, researchers were able to separate the emission into three physical components with characteristic temperatures of 550, 1150, and 1600 K that they associated with gas at different distances from the central star. These high spectral-resolution data reveal a more accurate estimate of the CO₂ abundance in the layers of the circumstellar envelopes of AGB stars than previous space-based observations. The results not only enable refinements on the chemical networks and abundances, but also open up new challenges for the understanding of circumstellar-envelope chemistry. These observations of the CO₂ lines among the forest



Ro-vibrational diagram of the strongest observed CO₂ bands in R Leo. The chosen stellar effective temperature is 2750 K, with a continuum flux peaking at ~2.5 μm, which causes the initial radiative excitation of the CO₂ molecules up to high energy vibrational states through the bands at 2.7 μm and 4.2 μm. (Fonfria et al. 2020)

of atmospheric features would not have been possible without the high spectral resolution of EXES operating aboard the SOFIA airborne observatory. ■

Galactic Chimneys: An Unseen Component of the Disk-Halo Interaction

(continued from page 9)

to 2 kpc from the midplane with a scale height intermediate between those of HI 21-cm, which traces extended tidal interactions, and mid-infrared PAH emission, which traces the star-forming disk.

The [C II] scale height is greater for the segment of NGC 891 that has a current burst of star formation, as compared to a more quiescent portion of the galaxy. Also there is some spatial association between the H α emission that traces ionized columns above the most-active star-forming regions: it appears [C II] traces molecular gas that has been elevated from the midplane and comprises the inner walls of chimneys that are illuminated by the remaining young stars in the cluster. The amount of material required to explain the extra-planar [C II] is much larger than required for the HI and H α . Researchers conclude that the new observations show a formerly unseen component of

the disk-halo interaction of the galaxy.

Researchers find that the spatial distribution of [C II] is best described by a two-component model. Each galaxy has a thinner disk with a scale-height of about 0.3 kpc. The central and active star-forming regions are supplemented by a thicker disk with a scale height of about 2 kpc.

The [C II] is far more extended than mid-infrared emission, which traces present-day massive star formation, but not as extended as the HI 21-cm emission, which traces low-metallicity circum/inter-galactic matter. The extra-planar [C II] may arise in walls of chimneys that connect the disk to the halo, where material is driven upward by stellar winds and supernovae. With these new observations, researchers see evidence for an unexpectedly large amount of material being involved in blowouts — that the walls of the chimney are surprisingly massive. ■

The Warped Magnetic Field of Centaurus A

(continued from page 3)

active nucleus is located within a chaotic dust lane, a warped remnant of the spiral galaxy that cuts the halo of the elliptical in half. At a close astronomical distance of only 3.4 Mpc, Centaurus A represents one of the best laboratories to study the effects of galaxy mergers on magnetic fields. Thus, Centaurus A can be used as an analog of mergers in the early universe.

SOFIA recently observed the warped molecular disk of Centaurus A with the High-resolution Airborne Wideband Camera-plus (HAWC+) at 89 μm with an angular resolution of 7.8" (~ 125 pc). These observations show that the magnetic field orientation is tightly aligned with the disk. Since the dust lane is a remnant of the spiral galaxy, a large-scale regular field should be present, but when a three-dimensional large-scale regular field was fit to the observations, results show that the dispersion of the observed magnetic field orientations are larger than the uncertainties associated to each measurement. Thus, another mechanism

must be producing the angular dispersion in the magnetic field orientations across the warped disk.

Since dynamos convert kinetic to magnetic energy, the measurements of the velocity dispersion of molecular gas can be used as a proxy for the quantification of the turbulence gas. Results show that the thermal polarization observed with HAWC+ decreases with increasing velocity dispersion, which is higher in the warped disk than in other areas of the galaxy. This result implies that turbulence gas at scales smaller than the angular resolution of the observations are distorting the original large-scale regular magnetic field from the spiral galaxy. The interpretation is that the small-scale turbulent fields are relatively more important across the warped disk than large-scale regular fields. These results imply that SOFIA has observed the small-scale fields in action, which may explain the enhancement of the magnetic fields over cosmic time. ■

SOFIA Comet Studies Explore the Carbon Gradient in the Solar System

(continued from page 8)

SOFIA Telescope (FORCAST) instrument with its suite of gratings can spectroscopically observe the emission emitted from the coma of comets at mid-infrared wavelengths (from 6 to 40 μm) that host a variety of solid-state spectral features arising from dust compositions including amorphous and crystalline silicates.

Thermal model analysis of the SOFIA-observed infrared spectral energy distribution revealed that Comet Catalina is an example of a subset of comets with weak silicate features and high C/Si ratios. The thermal emission from their coma is dominated by warmer particles that are significantly more absorbing at UV-near-IR wavelengths than silicates. The FORCAST spectral band provided a constraint that required the presence of amorphous carbon as a dominant constituent of the coma particle population. This analysis suggests that a carbon-rich reservoir existed in the regimes of comet formation.

Jupiter, with its enormous size and gravitational forces, created a dividing line between the carbon-poor inner regions and carbon-rich outer regions of the solar nebula, preventing mixing between them. Researchers think that

a slight change in Jupiter's orbit allowed small, early precursors to comets to deliver carbon from the outer to inner regions, where it was incorporated into the formation processes of the rocky planets. This delivery possibly occurred during the early pebble accretion phase of primordial disk evolution when the motions of aggregating materials, including comet dust grains, are dominated by inward pebble drift contemporaneous with initial coalescence of comet nuclei.

As we observe more comets with SOFIA, including dynamically new comets, will a significant population of carbon-rich comets arise? If so, the challenge will be to fold these discoveries into protoplanetary disk mid-plane models of processing of primitive materials, migration of refractory dust, volatiles, and organic species as planets grow, and accretion seeding of evolving rocky worlds in the habitable zones. Confirmation of how comets and asteroids delivered these materials and pre-biotic precursors to the terrestrial planet zone, potentially catalyzing life, may soon be within reach. ■

EXES Probes the Heart of Hot-Core Chemistry

(continued from page 4)

temperatures in pre-stellar clouds and increases towards later stages in star-formation; thus this ratio can be used as a chemical clock.

Hot cores associated with high mass protostars are a rich source of chemistry in the interstellar medium (ISM) and known to harbour molecules such as HCN and HNC. They represent a key stage in stellar evolution as a young protostar heats its natal, icy mantles to unlock reservoirs of molecules.

Despite being the first hot molecular core discovered, IRC2 is atypical. Most hot cores envelop high mass protostars and are internally heated, while IRC2 is heated externally. An explosive event in the Orion BN/KL region 500 years ago possibly separated IRC2 from the protostar called Radio Source I. Radio Source I has no MIR component and is presently obscured by dust.

The derived ratio from the EXES spectra, HCN/HNC=72, offers insight into the origins of IRC2. A gas-grain chemical network was utilized to model the evolution of HCN/HNC in three phases: free fall collapse, warmup, and post warmup. The model reaches the derived HCN/HNC after 10^6 years, suggesting that the hot core's origin predates the explosive event. It is likely that Radio Source I was once embedded in IRC2 and heated it to reach HCN/HNC=72.

The derived $^{12}\text{C}/^{13}\text{C}=13$ is lower than most measurements in the sub-mm/mm and radio, and over five times lower than expected for Orion's galactocentric distance. This ratio is similar, however, to that derived from C_2H_2 measurements, also from EXES. If the HCN lines were

optically thick and the HCN column density underestimated, this could explain this low ratio. However, the data do not show any of the expected signs of optically thick lines, suggesting that galactocentric distance may not be the only factor affecting the ratio.

Previous observations at longer wavelengths detected colder components of these three molecules in emission, while the MIR observations are hotter and in absorption. EXES's smaller beam size allows us to focus on the hot core itself without confusion from surrounding sources.

All three molecules arise in cooler 100–200 K gas that is moving at a velocity similar to the outflow from the nearby high mass protostar Radio Source I, and are likely associated with it. There is also a second warmer HCN component at a separate velocity, the closest detection ever to the heart of the hot core itself. These results show that SOFIA allows us study the chemistry and physical conditions closest to the protostars without spatially resolving them.

The work presented here is part of a wider molecular survey of Orion IRC2 with EXES spanning 7.2 to 8 and 13.2 to 28.3 μm . The survey has detected a forest of molecular transitions in this wavelength region. Researchers are currently identifying and using them to build an inventory of molecules in the MIR to complement line surveys in other wavebands. Such comprehensive line surveys not only create a rich legacy archive, but also provide a valuable reference database for future James Webb Space Telescope observations. ■

First Signs of Star Birth Triggered by Orion Wind

(continued from page 7)

will be lost to future star formation, the molecular globules may provide conditions suitable for the birth of new low-mass stars. In fact, one of the globules coincides with a known protostar. The masses of the globules, derived from the CO(2-1) lines, however, are only one solar mass or less, much lower than the mass needed to trigger their gravitational collapse. The analysis indicates that the shell surrounding the Orion Nebula will most likely not form new stars, but different outcomes may result in other

star-forming regions with varying circumstances.

The [CII] line proves to be an ideal means for the study of stellar feedback in a wide range of conditions. Together with CO line observations, the complex interplay between neutral atomic and molecular gas under the influence of massive stellar winds and radiation can be explored. Wide-field mapping at high spectral resolution, such as provided by SOFIA and the IRAM 30-meter telescope, is required. ■

Magnetic Highway: Channeling the M82 Superwind

(continued from page 6)

reduces to zero at infinity and generates the measured field at the photosphere.

We have modified the solar potential field method to work with the HAWC+ data in order to extrapolate the core field and investigate the potential magnetic structures in the halo of M82. The two-dimensional Cartesian set up places the center of M82 at $(x,z) = (0,0)$ and the galactic plane along the x-axis. The first boundary condition involves the B-field values determined from the map described below at $B(x,0)$ and the second, like the solar case, assumes that $B(x,\infty) = 0$.

We used the HAWC+ polarimetric data from SOFIA and the Davis-Chandrasekhar-Fermi (DCF) method to estimate the plane-of-the-sky magnetic field strength in the central starburst region of M82. This method relates the line-of-sight velocity dispersion and the plane-of-sky polarization angle dispersion. It assumes an isotropically turbulent medium whose turbulent kinetic and turbulent magnetic energy components are in equipartition. Using mean values of mass density, velocity dispersion, and polarization angle from the literature and, for the first time, modifying the DCF approximation to account for the galactic superwind by adding a steady-flow term to the wave equation, we find that the average magnetic field within the starburst region is 0.77 ± 0.45 mG.

We also defined the *Turbulent Plasma Beta*, β' , as the ratio of thermal-plus-turbulent pressure to magnetic pressure and estimate $\beta' = 0.56 \pm 0.23$. We can then use the pixel-by-pixel values of the mass density and velocity dispersion to construct, for the first time, a two-dimensional map of the magnetic field strength in the inner regions of M82. We input the B-field values along the galactic plane into the modified potential field extrapolation code. The resulting magnetic field structure is shown in the figure on [page 6](#).

These results indicate that the observed turbulent

magnetic field energy within the starburst region is composed of two components: a potential field arising from the galactic outflow and a small-scale turbulent field arising from a bow-shock-like region. This result represents the first detection of the magnetic energy from a bow shock in the galactic outflow of M82.

The results of the potential field extrapolation allow us to determine, for the first time, if the field lines are open or closed. Since the turbulent kinetic and magnetic energies are in close equipartition at 2 kpc (measured) and 7 kpc (extrapolated), we conclude that the fields are frozen into the ionized outflowing medium and driven away kinetically. These results indicate that the magnetic

field lines in the galactic wind of M82 are open, providing a direct channel between the starburst core and the intergalactic medium. The powerful winds associated with the starburst phenomenon appear to be responsible for injecting material enriched with elements like carbon and oxygen into the intergalactic medium.

Magnetic fields generated by turbulent gas motions arising from galactic outflows, mergers, and active galaxies may

permeate the intergalactic medium. Here, we used the HAWC+ data and a potential field extrapolation to trace the magnetic fields in the galactic outflow of M82 and quantify how these fields may magnetize the intergalactic medium. We demonstrated that far infrared polarization observations provide a powerful tool to study the magnetic field morphology in galactic outflows. Ongoing efforts like the SOFIA Extragalactic Magnetic Fields Legacy Program will provide deeper observations of the large-scale magnetic field structure in the disk of M82 as well as other nearby galaxies. This work serves as a strong reminder of the fundamental importance of magnetic fields, often completely overlooked, in the formation and evolution of galaxies. ■

The results of the potential field extrapolation allow us to determine, for the first time, if the field lines are open or closed.

Episodic Accretion in Massive Star Formation

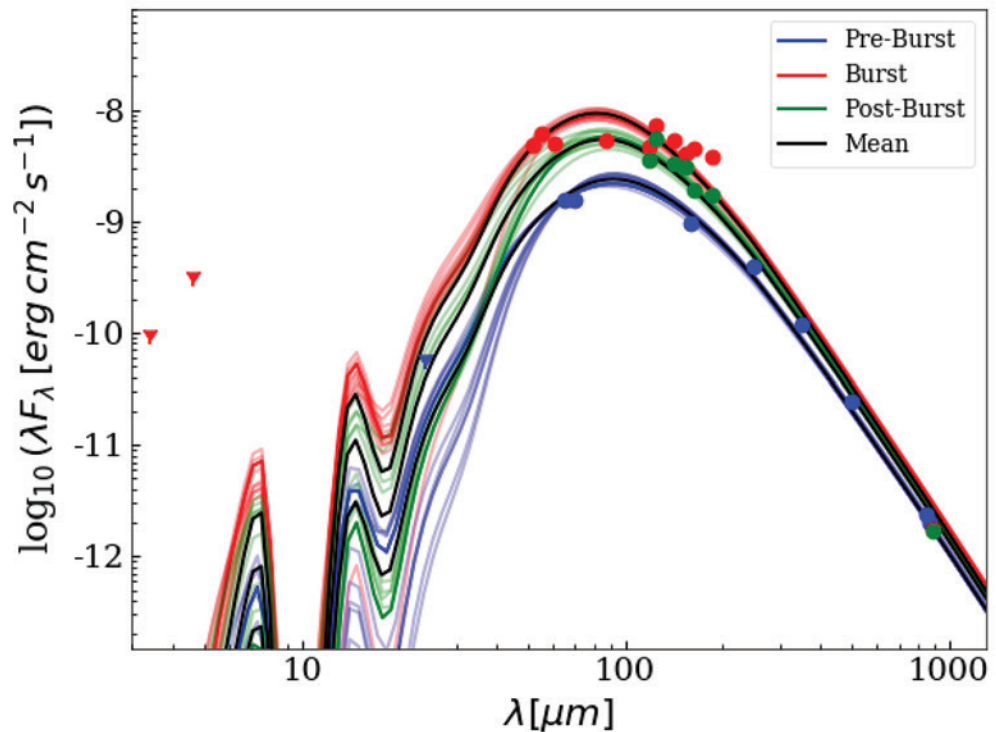
(continued from page 5)

increase in brightness as well as the subsequent slow decay. During the growth spurt, the source emitted about five times more energy than in the quiescent state.

The infrared data obtained by SOFIA were crucial in deriving fundamental parameters of the accretion burst such as the mass accreted during the event and the total energy released by the burst. Radiative transfer modeling yielded major burst parameters and suggests that the circumstellar disk may be transient. The significant changes to the spectral energy distribution in the infrared also allowed astronomers to exclude other physical processes, such as varying obscuration, that might be responsible for the luminosity variations.

SOFIA also detected a similar but less luminous accretion event in the low-mass star FU Orionis as well as a high-luminosity accretion event in S255IR. Observations of S255IR, a protostar of 20 solar masses, established both the mass accreted (~ 2 Jupiter masses) and the energy released (~ 1046 erg) during the burst, three orders of magnitude higher than any previously observed accretion event from lower mass stars. Presumably such accretion bursts, while rare for an individual object, often occur somewhere, due to the large number of protostars in this phase. Accurate measurements of the accreted mass and the luminosity of future stochastic accretion events would not be possible without SOFIA.

The verification of the accretion burst from G358 is another confirmation that methanol maser flares provide reliable alerts for such events. Thus, monitoring of these masers greatly enhances the chances of identifying massive young stellar objects during periods of intense growth. The few events known to date already indicate a broad range in burst strength and duration as well as environmental characteristics.



Strength of the radiation of the young massive star G358 as a function of the wavelength. Dots mark measured values from FIFI-LS/SOFIA (red & green) and PACS/Herschel satellite (blue) and lines the modeled emission of the object. The colors mark points in time, with blue meaning before the stochastic accretion event, red during (SOFIA flight 1) and green, 18 months after (SOFIA flight 2). (Stecklum et al. 2021)

These results substantiate the predictions of disk fragmentation models and radiation hydrodynamic simulations while ruling out alternatives like stellar mergers. The data also confirm that high-mass stars may form like their less massive siblings, namely from collapsing interstellar gas and dust clouds, ultimately gathering the in-falling material in an accretion disk. Moreover, the new observations provide strong evidence of episodic accretion in young massive stars. Since the matter distribution in the accretion disk appears to be clumpy rather than continuous, disk fragments are occasionally ingested onto the growing star, causing eruptions. These new findings confirm that the formation of high-mass stars can be considered a scaled up version of the process by which low-mass stars like our Sun are born. The main differences are that massive stars would form with larger disks, higher accretion rates, and on much shorter time-scales (around 100,000 years instead of several million years). ■

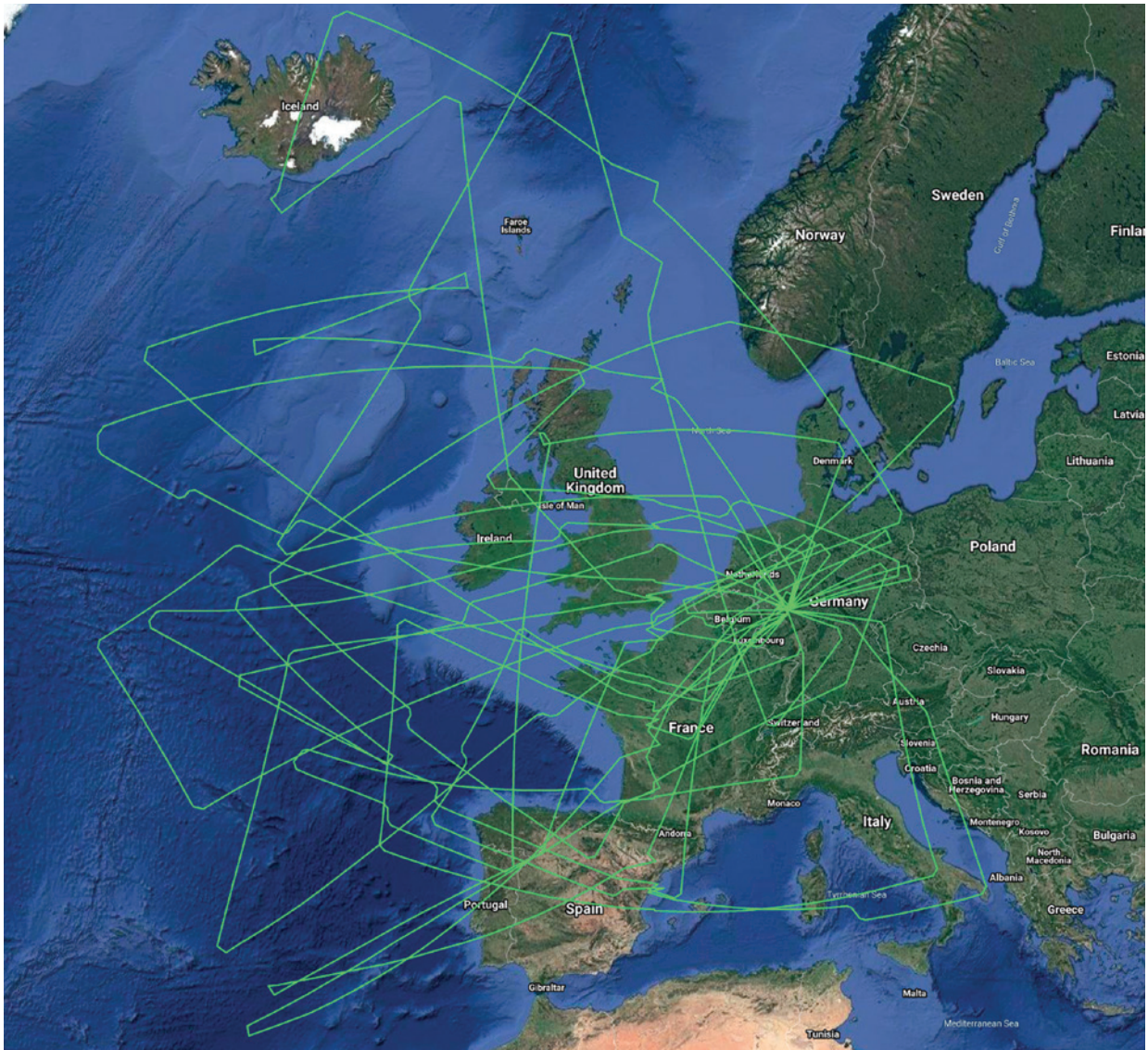


Image of flights from the SOFIA Germany deployment in February and March, 2021. The observatory took advantage of its proximity to science teams at the Max Planck Institute of Radio Astronomy in Bonn and the University of Cologne, which operate the GREAT instrument, to conduct research flights from the Cologne Bonn Airport. Over the course of six weeks, SOFIA conducted 15 overnight research flights that focused on high-priority observations, including how stars can transform galaxies and what is the origin of cosmic rays in the Milky Way galaxy. *Map data ©2021 GeoBasis-DE/BKG (©2009), Google Imagery ©2021 NASA, TerraMetrics*

SOFIA is a Boeing 747SP jetliner modified to carry a 106-inch diameter telescope. DLR is NASA's partner on SOFIA, providing the telescope, scheduled aircraft maintenance, and other support for the mission. Ames manages the SOFIA program, science, and mission operations in partnership 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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