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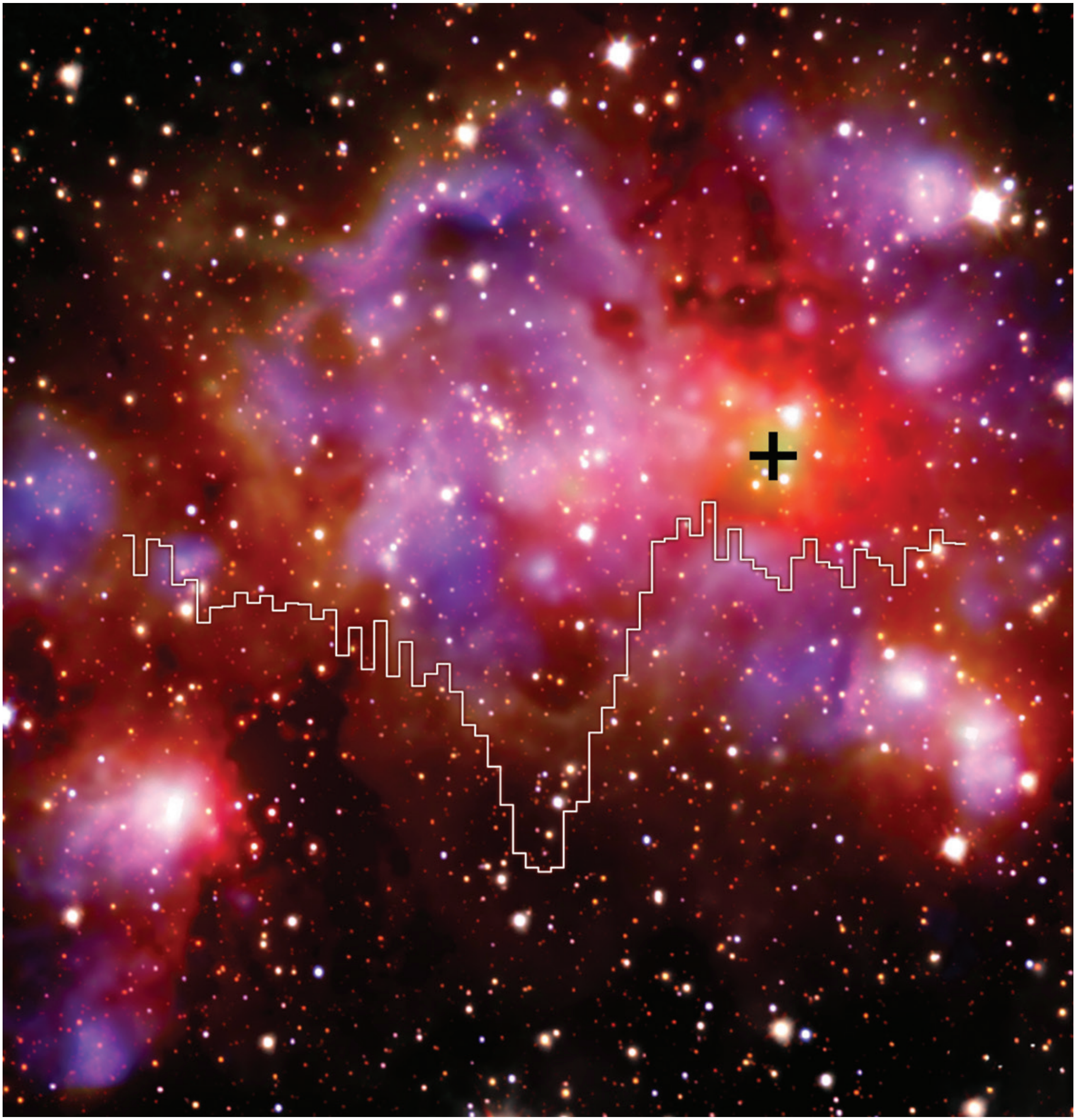

The two-component OD absorption spectrum from GREAT superposed on a three-color image of W49A. See Science Spotlight, page 3.
(De Buizer et al. 2021/SOFIA/Herschel/ESO/Csengeri et al. 2022)

The Stratospheric Observatory for Infrared Astronomy, or SOFIA, gathers data to investigate fundamental astrophysical phenomena and objects such as star birth and death, formation of new stellar systems, organic compounds in space, magnetic fields, and black holes, as well as planets, comets, and asteroids in our solar system.

SOFIA's instruments operate in the near-, mid-, and far-infrared wavelengths. SOFIA flies into the stratosphere at 38,000–45,000 feet, above 99 percent of Earth's infrared-blocking atmosphere, letting astronomers study celestial sources 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 Photo-Dissociation Regions to magnetically driven flows around a supermassive black hole.

The SOFIA Science Center offers a suite of tools and documentation to facilitate data analysis and proposal submission, available at www.sofia.usra.edu. Support is provided through the HelpDesk: sofia_help@sofia.usra.edu

Proposal Submission

Observing proposals are solicited from the U.S. and international astronomy communities through regular Calls for Proposals and Director's Discretionary Time. The latest Call for Proposals 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, providing detailed information about the instruments and observing modes that will be available for observations during the relevant cycle.

All SOFIA proposals are prepared and submitted using the Unified SOFIA Proposal and Observation Tool (USPOT). 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).

Data Archive

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.

SOFIA data is stored on the IPAC Infrared Science Archive (IRSA). Access the SOFIA webpage on IRSA at https://irsa.ipac.caltech.edu/Missions/sofia.html

Data Analysis

The Pipeline User Manuals and Guest Observer Data Handbooks describe the archival data products, processing steps, calibration procedures, and known issues.

Information about how to reprocess archival data through the pipeline is available from the pipeline's GitHub repository. A series of pipeline tutorials is also available.

Data analysis cookbooks and Instrument FAQs are available to guide users through typical uses of SOFIA data and address common questions. The recorded lectures from the 2022 SOFIA School provide more information on scientific analysis and interpretation of data. ■

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SOFIA SENIOR SCIENCE LEADERSHIP

Margaret Meixner, *Science Mission Operations Director*
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William T. Reach, *Associate Director for Science Operations*

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Science Spotlight

Timea Csengeri, *University of Bordeaux*
Joan Schmelz, *Universities Space Research Association*

Deuterated Hydroxyl as a Star Formation Tracer

Water is one of the most important molecules in the processes that govern star and planet formation. Although the relative importance of its creation and destruction mechanisms in the interstellar medium are still debated, the large water content of the Earth's atmosphere limit direct measurements of its abundance variations. Fortunately, observations of the hydroxyl radical, OH, can constrain chemical pathways leading to the production of the water molecule. In addition, tracing the deuterated form, OD, can place constraints on the chemical formation routes by measuring the quantity of the enhancement of deuterium-containing molecules in the star-forming gas. The OD/OH ratio is also an important probe since it may reflect the physical conditions and the chemical evolutionary state of the gas.

The two-component OD absorption spectrum from GREAT superposed on a three-color image of W49A; SOFIA-FORCAST 20 μm (blue), SOFIA-FORCAST 37 μm (green), and Herschel-PACS 70 μm (red). Stars are from Spitzer-IRAC 3.6 μm (white). The plus sign marks the position of the spectrum. *(De Buizer et al. 2021/ SOFIA/Herschel/ESO/Csengeri et al. 2022*

Rotational transitions from the OH and OD molecules lie in the THz band and can be probed with the German Receiver for Astronomy at Terahertz Frequencies (GREAT) instrument onboard SOFIA. Previous observations of OD absorption were limited to a single source, but results from this work have added 13 new OD detections toward a wide variety of galactic targets, including cold quiescent clouds as well as more evolved regions with ionizing OB type stars. Researchers aim to constrain the OD abundance and infer the deuterium fractionation of OH in the molecular envelopes. Radiative transfer modeling using multiple tracers shows that the OD absorption likely

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About this Spotlight

Paper: SOFIA/GREAT observations of OD and OH rotational lines towards high-mass star forming regions
Authors: T. Csengeri, F. Wyrowski, K. M. Menten, H. Wiesemeyer, R. Güsten, J. Stutzki, S. Heyminck, and Y. Okada
Reference: A&A 658, A193 (2022).

Youngmin Seo, *NASA-JPL/CalTech*
Joan Schmelz, *Universities Space Research Association*

Role of Magnetic Fields in Cloud Destruction in the Keyhole Nebula

High-mass star formation is a fundamental process that drives the life cycle of the interstellar medium (ISM) and the evolution of galaxies. The majority of stars form within high-mass clusters, where stellar feedback generates turbulence and provides the energy to transform one phase of the ISM into another. Extreme star-forming regions that are well resolved provide unique analogs to the starburst period of galaxy evolution. Thus, probing the detailed processes within these regions in the Milky Way is crucial for understanding more generally how galaxies evolve.

The magnetic field is one of the crucial elements regulating physical processes in star-forming regions. It may regulate the star formation rate and efficiency by providing support against self-gravity in giant molecular clouds and cloud cores. Magnetic fields in cloud cores are inherited by protoplanetary disks and affect planet formation. Low-mass star-forming regions exhibit a clear trend where magnetic fields are parallel to the long axis in low-density filaments and perpendicular to the long axis in high-density filaments.

Magnetic field streamlines detected by SOFIA are shown over an image of the Keyhole Nebula, part of the larger Carina Nebula, imaged with the ESO 3.6-metre telescope on La Silla. *(NASA, the SOFIA science team, Y. Seo; ESO)*

Observations to date show that magnetic fields in high-mass star-forming regions are typically ordered (perpendicular or parallel) to the morphologies of bright-rimmed clouds, bars, pillars, or cometary globules. They also show a more complex structure than those in low-mass star-forming regions, demonstrating that magnetic fields can be altered by the effect of stellar feedback. However, little is known about the role of magnetic fields in the evolution of molecular clouds and the life cycle of the ISM by stellar feedback.

About this Spotlight

Paper: Probing Polarization and the Role of Magnetic Fields in Cloud Destruction in the Keyhole Nebula
Authors: Y. Seo, C. D. Dowell, P. F. Goldsmith, J. L. Pineda, and L. Majumdar
Reference: 2021 ApJ 917 57.

The Carina Nebula complex, with its ~70 O-type stars, is the most energetic star-forming region in the Milky Way. The Keyhole Nebula is only 1.3 pc away from

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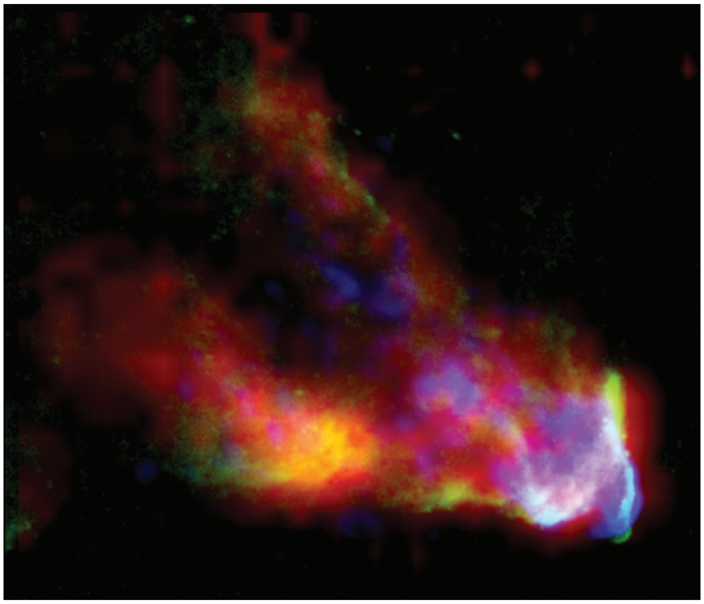
Archana Soam, *Indian Institute of Astrophysics*
Joan Schmelz, *Universities Space Research Association*

Temperature and Density Layers in the Ghost Nebula

The high-energy radiation from new-born massive stars imposes physical and chemical changes on the surrounding clouds of gas and dust. These Photo-Dissociation Regions (PDRs), where far-ultraviolet radiation controls the gas heating and molecular dissociation, are astrophysically important sites in the evolution of the interstellar medium (ISM), including star formation and cloud destruction. While several models of PDR physics have been developed, a number of important detailed assumptions including the clumpiness, temperature structure, and reaction network remain uncertain. Progress requires additional observational constraints, especially those related to the micro-structure of the regions, so spatial resolution is vital.

Molecular hydrogen is readily detectable in PDRs. Transitions results from the exposure to the light from O/B stars and the interstellar radiation field. Far-UV pumping, photo-dissociation, and photo-electric emission are critical processes. Collisional de-excitation of hydrogen molecules initially excited by UV photons also contributes to the heating.

Using the narrow slit of the Echelon-Cross-Echelle Spectrograph (EXES) instrument and the accurate pointing of SOFIA, researchers observed the Ghost Nebula (IC63), a well-studied PDR at a distance of ~200 pc and irradiated by the light from γ Cassiopeia, a B-type star. Combining the high-resolution molecular hydrogen spectroscopic observations from EXES with existing H_2 fluorescent observations from the Canada-France-Hawaii Telescope, researchers were able to resolve the temperature and density structures of a PDR for the first time.



Three-color image of the Ghost Nebula with C^+ emission from SOFIA/upGREAT (red), molecular hydrogen fluorescence from the Canada-France-Hawaii Telescope (green), and HCO^+ gas emission from CARMA (blue). The *ridge* described in the text is the green-white vertical structure in the lower right corner. *(Soam et al. 2021)*

The PDR was divided into three regions for analysis based on the illumination from γ Cas: *sunny*, where hydrogen exists mainly in atomic form because most of the molecular hydrogen is photo-dissociated by the high-energy UV photons; *shady*, where hydrogen exists in molecular form and transitions are readily detectable; and *ridge*, the boundary between the two highlighted by near-infrared line emission. By placing the EXES slit on these three locations, researchers hoped to measure the small-scale temperature changes in the gas.

Although H_2 emission was not detected on the *sunny* side of the ridge, likely due to the photo-dissociation of molecular gas, temperatures of 495 K and 562 K were

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About this Spotlight

Paper: Spatial Variation in Temperature and Density in the IC 63 PDR from H_2 Spectroscopy
Authors: A. Soam, B-G Andersson, J. Karoly C. DeWitt, and M. Richter
Reference: 2021 ApJ 923 107.

Science Spotlight

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

Magnetically-Driven Flows in NGC 1097

Magnetically-driven flows feed the super massive blackhole at the center of NGC 1097. SOFIA investigated this long-standing problem of the large-scale transfer of matter from the body of the host galaxy to the active nucleus.

Observations indicate that around two-thirds of spiral galaxies have bars that may affect the transfer of matter. The bar creates non-circular motions, increasing particle collisions that dissipate energy and cause the gas to lose angular momentum and move inward. This moving gas may trigger a starburst ring and eventually feed the active nucleus. However, hydrodynamics models using this gravitational-potential scenario have difficulty reproducing the observed gas inflows.

Magnetohydrodynamic models can provide an alternative solution. Galactic bars and nuclear rings have strong magnetic fields, where the magnetic forces dominate the gas flows in the spiral and bar structures. The non-circular motions in bars interact with magnetic fields, and the magnetic stress removes angular momentum from the gas. The dominant magnetic fields then deflect the gas flow from the galactic bar to a new orbit, producing a central ring and/or central spiral towards the nucleus. The gas can then flow towards the active nucleus, which ultimately feeds the super massive black hole. However, the magnetic flows in the central region of galaxies have not been characterized until now.

NGC 1097 is a barred spiral galaxy with a starburst ring surrounding an active galactic nucleus. Herschel observed the total thermal emission arising from the starburst ring. Although these observations were able to characterize the efficiency of the star formation, there was no clear evidence of flowing material towards the galactic center. Radio polarimetric observations have shown that NGC 1097 has the strongest magnetic field strength of any observed spiral galaxy. This magnetic field dominates the transfer of gas from the spiral to the starburst ring,

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Magnetic field streamlines from the Effelsberg radio telescope superposed on an image of the central 1 kpc starburst ring of the spiral galaxy NGC 1097 obtained with the NACO adaptive optics on the VLT. Gas streams follow the magnetic field, feeding the super massive black hole with matter from the galaxy. The image was constructed by stacking J- (blue), H- (green), and Ks-band (red) images. *(NASA, the SOFIA science team, E. Lopez-Rodriguez et al.; ESO/Prieto et al.)*

About this Spotlight

Paper: Extragalactic Magnetism with SOFIA (Legacy Program) - II: A Magnetically Driven Flow in the Starburst Ring of NGC 1097*
Authors: E. Lopez-Rodriguez, R. Beck, S. E. Clark, A. Hughes, A. S. Borlaff, E. Ntormousi, L. Grosset, K. Tassis, J. E. Beckman, K. Subramanian, D. Dale, and T. Díaz-Santos
Reference: 2021 ApJ 923 150.

Science Spotlight

Elizabeth Tarantino, *University of Maryland - College Park*
Joan Schmelz, *Universities Space Research Association*

Multi-Phase [C II] Emission in Nearby Galaxies

The [C II] fine-structure transition at 158 μm is one of the brightest far-infrared spectral lines, a major coolant of the molecular and atomic gas, and a tracer of star formation in galaxies both nearby and far away. Although observations of [C II] are used routinely as a tool to study gas in galaxies, the interpretation of [C II] data can be complex due to its multi-phase nature. In fact, recent observations from SOFIA in the two nearby spiral galaxies, M101 and NGC 6946, reveal that less than half of the [C II] emission may originate in the molecular gas associated with star formation.

Understanding the cycle between star formation and the interstellar gas is a central question in astronomy. Line-integrated measurements of [C II] are often used to constrain properties of the star-forming processes, such as the molecular gas mass, in nearby galaxies. [C II] is even detected in very distance galaxies using the Atacama Large Millimeter Array (ALMA) when the line is red-shifted into the sub-millimeter band. These results help astronomers investigate the evolution of star formation over cosmic time.

Because the ionization potential of neutral carbon (11.3 eV) is less than that of hydrogen (13.6 eV), significant concentrations of [C II] can exist in neutral (molecular and atomic) and ionized gas. Therefore, to interpret observations of [C II], more information is needed to determine the fraction of emission that originates in each of these components of the interstellar medium.

Researchers used the unique capability of SOFIA/upGREAT to observe [C II] at very high spectral resolution where the profile of the [C II] line is resolved. The shape of the profile traces the bulk motions of gas along the line of sight and, combined with ancillary data, is used to determine which gas phase dominates the [C II] emission. SOFIA observed [C II] and [NII] in 18 different regions across M101 and NGC 6946 that probed a wide range of environments. The [NII] emission is only produced in the ionized gas and can determine the amount of [C II] associated with the ionized phase. Results indicate that the ionized gas contributes no more than 12% to the overall [C II] emission.

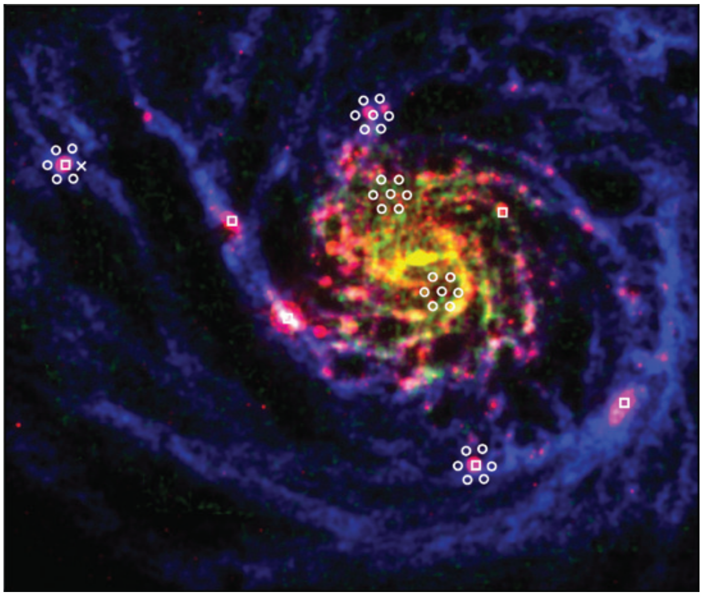

Image of M101 showing the 24 μm Spitzer emission from warm dust (red), the CO (2-1) emission from molecular gas (green), and the 21-cm HI emission that traces the atomic gas (blue). The pointings from SOFIA/GREAT are shown as white circles and squares, designating areas of high and low star formation, respectively. Pointing selection shows a range of environments, probing the metallicity gradient in each galaxy and different levels of star formation rate. *(Kennicutt et al. 2003 (SINGS survey from Spitzer/MIPS), Leroy et al. 2009 (HERACLES survey from IRAM 30-m), and Walter et al. 2008 (THINGS survey from VLA)).*

About this Spotlight

Paper: Characterizing the Multiphase Origin of [C II] Emission in M101 and NGC 6946 with Velocity-resolved Spectroscopy
Authors: E. Tarantino, A. D. Bolatto, R. Herrera-Camus, A. I. Harris, M. Wolfire, C. Buchbender, K. V. Croxall, D. A. Dale, B. Groves, R. C. Levy, D. Riquelme, J.-D T. Smith, and J. Stutzki
Reference: 2021 ApJ 915 92.

VLA HI interferometric and IRAM 30-m CO (2-1) spectra

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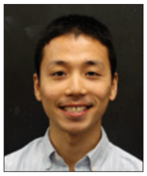
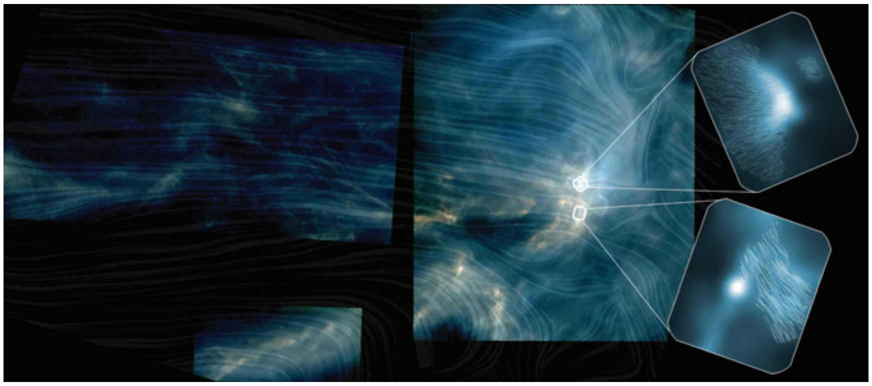
Science Spotlight

Dennis Lee, *CIERA /Northwestern University*
Joan Schmelz, *Universities Space Research Association*



Constraining Magnetic and Gravitational Energies in Star-Forming Clouds

Despite recent progress driven by improved observational capabilities, the role of magnetic fields in the stellar birth process remains poorly understood. Initial steps toward greater understanding resulted when data from the Planck satellite were used to construct magnetic field maps for ten relatively nearby star forming regions. By comparing the maps with the orientations of elongated structures, the Planck team discovered that the plane-of-sky magnetic field is preferentially parallel to the orientation of elongated structures at lower column densities but preferentially perpendicular at higher column densities. This transition is also seen in magnetohydrodynamic simulations, but only when they include reasonably strong magnetic fields. Simulations where the magnetic field is weak compared with turbulence showed no such transition.



The magnetic streamlines from Planck superposed on a three-color image of the Rho Ophiuchi cloud complex from Herschel. The higher-resolution insets from SOFIA/HAWC+ show clearly that the streamlines are oriented perpendicular to the structure. *(ESA/Herschel/Planck; J. D. Soler, MPIA; Lee et al. 2021)*

This critical transition was observed on spatial scales near the angular resolution limit of Planck. The HAWC+ instrument on SOFIA provides much higher resolution while still incorporating sufficient information at larger spatial scales to overlap with Planck. The combination, which extends from much larger to much smaller than the critical scale, allows the transition to be more fully characterized. For both Planck and HAWC+, the magnetic field structures are determined from the polarization of thermal emission from magnetically aligned dust grains.

The rate at which new stars are born within giant molecular clouds depends on complex interactions between gravity, turbulence, and the magnetic field. On the scales of clouds and cloud cores, a strong magnetic field can slow the collapse due to magnetic pressure/tension. On smaller scales, the field can transfer angular momentum away from infalling gas, facilitating protostellar collapse. Truly understanding the role of the magnetic field in star formation requires the ability to probe these fields across a range of spatial scales: from the clouds (tens of parsecs) down to the cores (< 0.1 pc) and below.

L1688, part of the Rho Ophiuchus cloud complex, is the closest site of clustered star formation to the Sun. The Planck and SOFIA observations together cover scales ranging from 3 pc (the size of L1688) down to 0.02 pc. While the Planck data for Ophiuchus are highly

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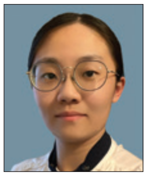
About this Spotlight

Paper: HAWC+/SOFIA Polarimetry in L1688: Relative Orientation of Magnetic Field and Elongated Cloud Structure
Authors: D. Lee, M. Berthoud, C. Chen, E. G. Cox, J. A. Davidson, F. J. Encalada, L. M. Fissel, R. Harrison, W. Kwon, D. Li, Z. Li, L. W. Looney, G. Novak, S. Sadavoy, F. P. Santos, D. Segura-Cox, and I. Stephens
Reference: 2021 ApJ 918 39.

Science Spotlight

Yingjie Cheng, *UMass Amherst*
Joan Schmelz, *Universities Space Research Association*



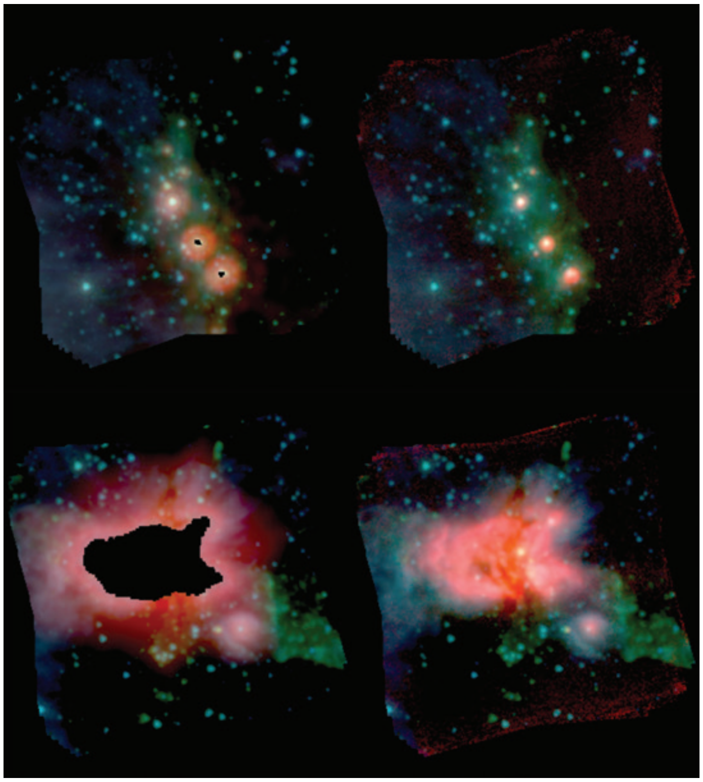
The Cygnus X Protostellar Luminosity Function

Large infrared surveys of molecular clouds have shown consistently that low-mass protostars are less luminous than expected from traditional star-formation models. The solution to this so-called 'luminosity problem' would shed light on some fundamental problems like the time required for a low-mass star to form. Since different star formation theories predict different protostellar luminosity functions, probing a large, unbiased sample of protostars could address these issues. Such a study hinges critically on obtaining a complete census of young stellar objects and extending their spectral energy distribution coverage through mid-infrared wavelengths.

The Cygnus X complex, one of the most active nearby star-formation regions, is a promising laboratory for this study. The huge protostar sample as well as the wide range of star-forming environments set the stage for not only completing the aggregate protostellar luminosity function, but also testing how it is affected by natal environment. Over 21,000 point sources have already been detected and identified as young stellar objects within Cygnus X as part of the Spitzer Extended Solar Neighborhood Archive, which provides uniformly produced mosaics, source catalogues, and corresponding completeness maps. However, the capacity of Spitzer to constrain the luminosity of bright sources is largely inhibited by confusion and saturation in its MIPS 24 μm data. In order to obtain the luminosities of bright, closely clustered protostars and in turn complete the luminosity coverage, new observations with the Faint Object InfraRed CAmera for the SOFIA Telescope (FORCAST) instrument on SOFIA are required.

About this Spotlight

Paper: Completing the protostellar luminosity function in Cygnus-X with SOFIA/FORCAST imaging
Authors: Y. Cheng, R. A. Gutermuth, S. Offner, M. Heyer, H. Zinnecker, S. T. Megeath, and R. Pokhrel
Reference: MNRAS, Volume 512, Issue 1.



RGB images of Cygnus X sub-regions with R=Spitzer MIPS 24 band (left) and SOFIA FORCAST 31 band (right) showing that bright, clustered regions can be completely saturated in the MIPS data, while clearly revealed by SOFIA FORCAST. The upper pair shows the saturated cores and strong halos of bright sources. The lower pair shows a close-up of a saturated area of extended nebulosity. *(Cheng et al. 2022)*

Since the FORCAST beam is much cleaner than the MIPS beam at large radii, its sensitivity gain for bright sources and nebulosity is frequently superior to MIPS. By combining bright protostars identified by FORCAST with the existing Spitzer catalogue, the coverage and luminosity estimates of bright protostars are greatly improved. Furthermore, differences among model predictions are

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Deuterated Hydroxyl as a Star Formation Tracer

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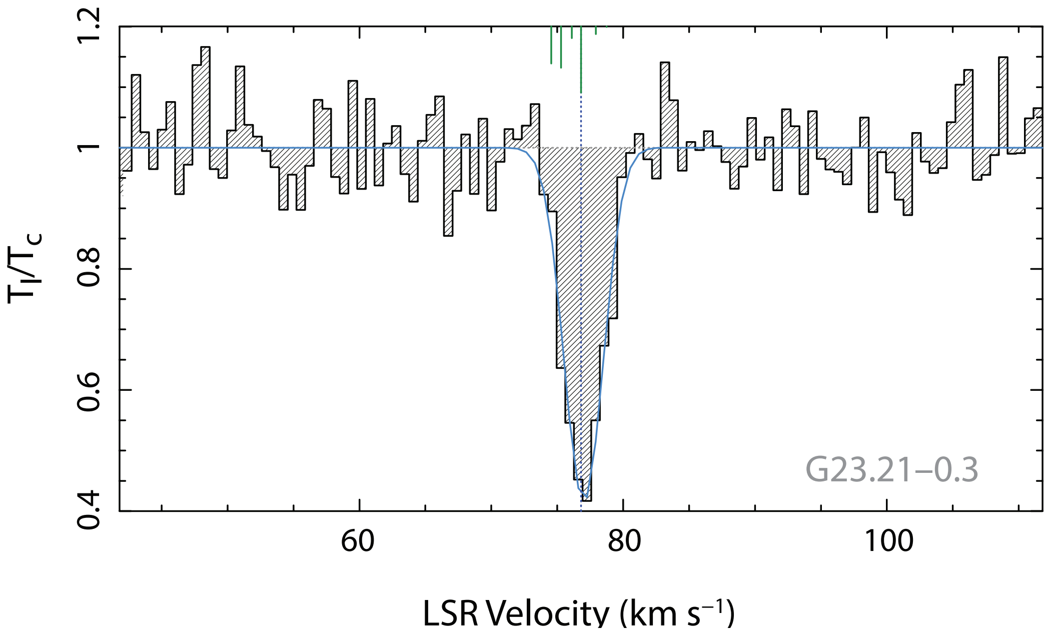
originates from the cold, outer layers of the star-forming gas and seems to be prevalent in massive clumps.

OD is identified toward all evolutionary stages of the targeted sample, suggesting a long lifetime for the molecule. However, data indicate that the OD abundance in the cold dense gas is higher at the onset of the cloud collapse and decreases with time. This is consistent with chemical models predicting that both higher temperatures and stronger radiation fields lead to a more efficient destruction of OD. Due to the radiative feedback of newly formed high-mass stars, such conditions occur towards the more advanced evolutionary stages of the formation process.



The line-to-continuum ratio for the OD $^2\Pi_{3/2}$ ground-state (J = 5/2-3/2) towards the quiescent source G23.21-0.3. *(Csengeri et al. 2022)*

Researchers find that the cold gas seen toward massive clumps typically exhibits a low deuterium fractionation, with a value of 0.5% toward the best-modeled source, G34.26+0.15. Although this value is lower than found towards nearby star forming regions using other molecules, it nevertheless corresponds to a significant enhancement of deuterium fractionation compared to the cosmic deuterium abundance of 0.015%. The enhancement of deuterium in molecules can be explained by chemical reactions proceeding at low temperatures.

A comparison between OD and the deuterated form of water, HDO, from Herschel and APEX data reveal similar line profiles for the entire sample. This would suggest that the two molecules, OD and HDO, may originate from the same gas. Furthermore, the deuterium fractionation for hydroxyl and water are similar, and a quantitative comparison between OD and HDO shows that their amount in the cold gas may be correlated. This would indicate that there is a strong link between the chemical reaction pathways of these molecules.

Although direct detections of the water molecule may be challenging, the regular and deuterated versions of the hydroxyl radical can aid in our understanding of the interstellar chemistry of star and planet formation, and ultimately, of the path to life. ■

Radiative transfer modeling using multiple tracers shows that the OD absorption likely originates from the cold, outer layers of the star-forming gas and seems to be prevalent in massive clumps.

Temperature and Density Layers in the Ghost Nebula

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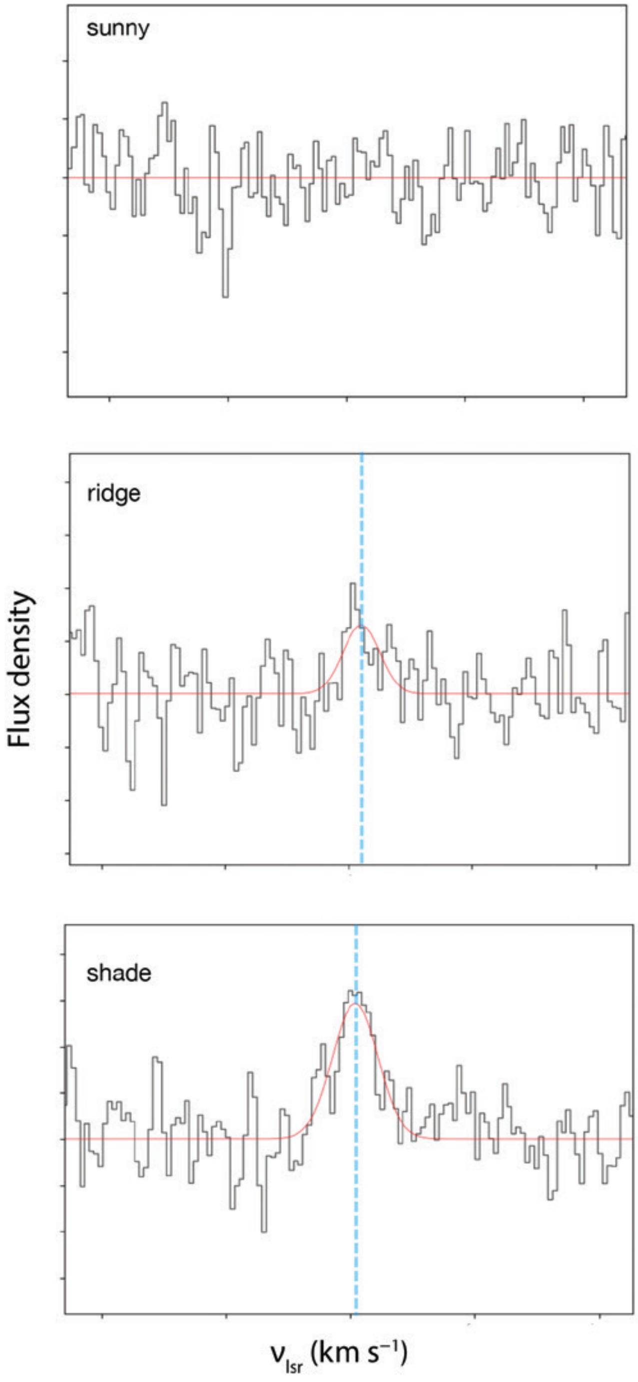
obtained toward the *shady* side and the *ridge*, respectively. The corresponding H_2 column densities are 3.6×10^{20} cm^{-2} and 9.8×10^{19} cm^{-2}. The emission was more prominent as EXES moves toward cooler and denser regions. The detected temperature gradient, which was correlated with the extinction into the cloud, demonstrates the capability of EXES to use H_2 pure rotational line spectroscopy to map the gas temperature on small scales.

> ***Although H_2 emission was not detected on the sunny side of the ridge, likely due to the photo-dissociation of molecular gas, temperatures of 495 K and 562 K were obtained toward the shady side and the ridge, respectively.***

The EXES temperatures are lower than the value obtained using lower spatial-resolution data from the Infrared Space Observatory. This difference indicates that the PDR is inhomogeneous and illustrates the need for high-resolution mapping of such regions to fully understand their physics. These results show that EXES/SOFIA is the only instrument capable of investigating the spatial variation in temperatures of PDRs.

EXES observations in combination with PDR models provide the best tool to study gradients in the physical properties of PDRs. With the success of this study, there are plans to observe other PDRs with EXES to obtain similar results that will lead to a better understanding of the physical and chemical process at work in these regions. ■



The H_2 emission line profiles for the *sunny, ridge,* and *shady* regions of the Ghost Nebula. No emission is detected in the sunny side of the PDR, showing the sharp photo-dissociation transition caused by the efficient self-shielding in H_2. The dashed blue line shows the center of the detected emission line and the solid red line shows the Gaussian fit. *(Soam et al. 2021)*

Role of Magnetic Fields in Cloud Destruction in the Keyhole Nebula

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η Carinae and is one of the clouds most severely affected by outbursts and X-rays. It contains a loop structure, which may have been formed by the powerful outflows from η Carinae that deformed the cloud. It is an excellent testbed in which to study the role of magnetic fields in a cloud undergoing extreme stellar feedback.

The High-resolution Airborne Wideband Camera (HAWC+) instrument provided a detailed polarization map of the dust continuum emission of the Keyhole Nebula. The observations reveal that the magnetic field orientation in the bar structure, which is not distorted by η Carinae, is almost identical to that of the large-scale magnetic field in the complex. On the other hand, the magnetic field in the loop is not correlated with the large-scale field structure. The orientation of the field in the region between the bar and the loop exhibits a fan shape that aligns with the direction of η Carinae's stellar wind. These features clearly demonstrate that the magnetic fields are disturbed by stellar feedback.

If magnetic fields are to regulate the cloud evolution against stellar feedback, the magnetic tension in the loop should be similar to the ram pressure of η Carinae's stellar wind. The polarization angle dispersion and the curvature of the loop seen using SOFIA show that the pressure exerted by the magnetic field tension in the loop is significantly weaker ($\sim 10^{-3}$) than the ram pressure of η Carinae's stellar wind. These results imply that while magnetic fields dominate during star formation, they play only a minor role in the cloud evaporation and destruction processes governed by stellar feedback. It will be interesting to see if these results for the Keyhole Nebula apply to other high-mass star-forming regions. ■

Magnetically-Driven Flows in NGC 1097

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but the magnetic field in the central region of NGC 1097 had not been fully studied.

SOFIA measured the magnetic fields in the starburst ring with HAWC+ at 89 µm with an angular resolution of 7.8″ (~720 pc). These observations in combination with the radio polarimetric observations have been able to trace the magnetic fields in the multi-phase interstellar medium in the starburst ring of NGC 1097. SOFIA traces the magnetic fields in the dense and warm interstellar medium, while radio polarimetric observations trace the magnetic fields in the diffuse and hot interstellar medium.

To investigate this problem, researchers used linear polarization decomposition, a new technique developed to analyze the Event Horizon Telescope observations of the magnetic fields surrounding the super massive black-hole of Messier 87. The decomposition of NGC 1097 data shows that the magnetic field has multiple components. The analysis reveals a constant magnetic field morphology in the dense interstellar medium located at the contact points of the galactic bar and the starburst ring as well as a spiral-like magnetic field morphology in the diffuse interstellar medium around and within the starburst ring. These results show, for the first time, the non-circular behavior of the magnetic fields in the multi-phase interstellar medium.

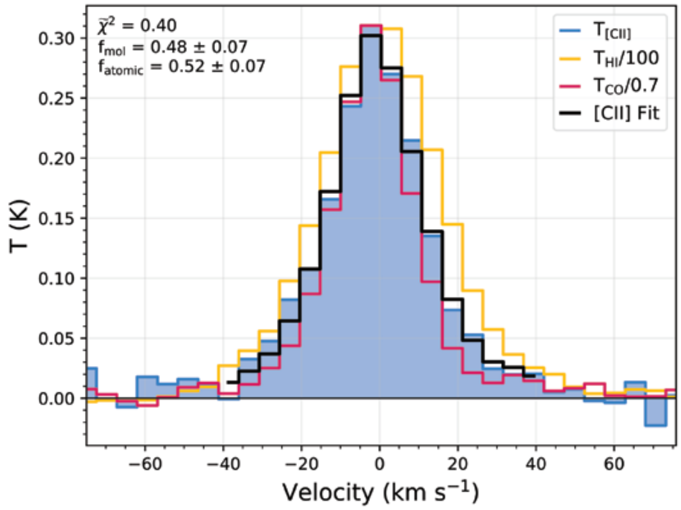
In addition, this work combined information on the gas flows and estimated the direction of the magnetic field using rotation measures. Analysis indicates that the spiral magnetic field is the signature of a galactic dynamo action outside and inside the starburst ring. This magnetic field coupled to the diffuse interstellar medium may be dragging material from the host galaxy to the center region. At the same time, the magnetic field in the dense interstellar medium is compressed with a constant orientation at the contact regions feeding the starburst ring.

This work shows that the magnetic fields control the transfer of matter from the starburst ring towards the active galactic nucleus and played a fundamental role in the evolution of NGC 1097. The SOFIA Legacy Program on Extragalactic Magnetism will provide a larger sample of galaxies to test whether these results are general or applicable only to the galaxies with the strongest magnetic field. ■

Multi-Phase [C II] Emission in Nearby Galaxies

(continued from page 7)

were used as decomposition templates for the atomic and molecular gas, respectively. Careful analysis reveals that the signal-to-noise in the [C II] data needs to be greater than 15 to achieve reliable decomposition results. This requires averaging individual GREAT spectra in regions of common characteristics such as high/low star formation rate and high/low metallicity. This comparison reveals that the molecular and atomic phases each contribute about equally to the [C II] emission on scales of about 500 parsecs. Measurements in the Milky Way and Magellanic Clouds, however, find that the atomic gas has a small (<15%) contribution to the [C II] emission on scales of about three to four parsecs. These results, taken together, suggest that the spatial scale of a measurement has a profound effect on the multi-phase nature of [C II] emission. At larger scales, more diffuse gas is averaged together with star-forming regions, producing a substantial component of [C II] associated with the atomic gas.



Averaged spectrum of the SOFIA/GREAT [C II] data (blue), with the ancillary CO (red) and HI (yellow) spectra. We decomposed the [C II] profile by fitting a combination of the CO and HI spectra shown in black, revealing that the [C II] originates from the molecular and atomic gas about equally. *(Tarantino et al. 2021)*

Researchers were then able to use the [C II] emission to determine the thermal pressure, an important measurement that can regulate star formation activity in galaxies, in the coldest atomic gas. The resulting values are higher than average thermal pressures measured in outer disk atomic gas regions, likely because the new measurements are able to probe both star-forming and quiescent regions. This shows how SOFIA can be used to determine important physical conditions of interstellar gas in unique ways.

The high proportion of [C II] coming from the atomic gas found in this study suggests that [C II] may be a poor molecular gas tracer. When using [C II] data at near and far redshifts, it is therefore necessary to consider how the multi-phase nature of [C II] emission will affect the analysis. ■

Constraining Magnetic and Gravitational Energies in Star-Forming Clouds

(continued from page 8)

suggestive of a transition in this region, the addition of the higher-resolution HAWC+ data at the high column densities provides confirmation. Therefore, the large-scale magnetic field in L1688 has an energy density comparable to or greater than that of turbulent gas motions.

By comparing the Planck and SOFIA measurements with a set of magnetohydrodynamic simulations of molecular clouds formed by colliding flows, researchers estimated the threshold volume density where the outward magnetic force balances the inward gravitational force. The value found for L1688 was approximately 10^4 molecules per cm^3, notably higher than a previously reported result made using line-of-sight estimates of the magnetic field from Zeeman splitting. One possible explanation for the discrepancy is cloud-to-cloud differences since the Zeeman estimate corresponds to an average across many clouds.

Looking forward, it is feasible to extend the methods applied here to other clouds. It is equally important to explore how the estimated threshold volume density might change with different simulation assumptions and observational constraints. These results will help deepen our understanding of the role of magnetism in star formation and how it may vary from cloud to cloud. ■

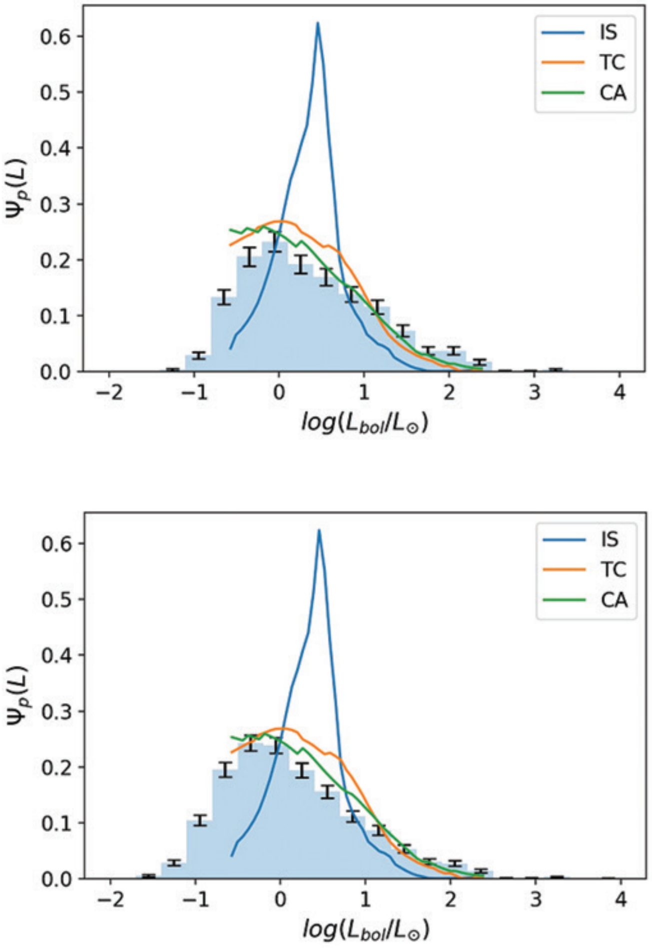
The Cygnus X Protostellar Luminosity Function

(continued from page 9)

best tested at the high luminosity end, so including the FORCAST data makes the comparison between observations and theories much more feasible.

An empirical relationship based on the mid-infrared spectral index and the mid-infrared luminosity is used to derive the bolometric luminosities of identified protostars. Then the protostellar luminosity function is simply the probability density distribution of the bolometric luminosities of all detected protostars. After accounting for possible contamination and incompleteness, the protostellar luminosity function in Cygnus X is well described by a power-law function with an index of around –0.5.

> ***Since the FORCAST beam is much cleaner than the MIPS beam at large radii, its sensitivity gain for bright sources and nebulosity is frequently superior to MIPS.***



Observed protostellar luminosity function for Cygnus X overlaid with theoretical models. The blue histograms show the observations. The blue curve represents the isothermal-sphere model, which clearly does not fit the observations. The turbulent-core (orange) and competitive-accretion (green) models both reproduce the general characteristics of the observations. *(Cheng et al. 2022)*

Previous work argued that the protostellar luminosity function in Cygnus X varies within molecular complexes and depends on the local environment in which protostars form. The improved sample results indicate that the protostellar luminosity function shows no dependence on temperature, but exhibits some excess at higher luminosities in regions of high stellar or gas density. These results are consistent with previous studies.

Researchers compared the observed protostellar luminosity function with predictions from three different models. The isothermal-sphere model assumes that gas accretes from an isothermal gas sphere on to the protostar at a constant rate determined by temperature. The turbulent-core model describes high-mass star formation in which stars form from turbulently supported cores within a gravitationally bound clump of gas. In the competitive-accretion model, stars accrete gas in the same gravitational potential until exhausted or ejected, so the accretion rate of each protostar depends on its mass and location within the clump of gas. The isothermal-sphere model does not reproduce the observed data. The lack of dependence on the gas temperature further supports the rejection of this model. Both the turbulent-core and competitive-accretion models fit the data well for constant accretion rates, but appear to over-predict the low-luminosity end and under-predict the high-luminosity end in regions of higher gas density. This may be an indication that episodic accretion as seen by SOFIA is an important aspect of star formation. ■

Nature Astronomy Covers Featuring SOFIA Results

Nature Astronomy's January 2022 issue editorial (And now we are five. Nat Astron 6, 1–2 (2022) https://doi.org/10.1038/s41550-022-01602-5) featured the five most popular covers for each year of the publication, voted by Twitter followers. Two of the five covers, pictured above, display SOFIA results. You can read more about magnetized filamentary gas flows in Serpens South in the January 2021 issue of *SOFIA Science* and about the warped magnetic field of Centaurus A in the June 2021 issue, both available at https://www.sofia.usra.edu/publications/sofia-science-newsletter. *(Top left image: NASA/SOFIA/T. Pillai/J. Kauffmann, NASA/JPL-Caltech/L. Allen; cover design: Bethany Vukomanovic; bottom left image: Enrique Lopez-Rodriguez; cover design: Bethany Vukomanovic)*

SOFIA at Chile's Santiago International Airport in March 2022 during a deployment to the Southern Hemisphere. This was SOFIA's first visit to South America, and its first short-term deployment, which lasted two weeks. During the deployment, SOFIA observed celestial objects that can only be seen from Southern Hemisphere latitudes, primarily the Large and Small Magellanic Clouds. *(NASA/Andy Barry)*

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.

SOFIA
Stratospheric Observatory for Infrared Astronomy

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