



# SOFIA Science

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# Remarkable Results



# Introduction

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

SOFIA investigates the physical, chemical, and dynamical processes at work in the formation of stars and planets. These data help us understand how massive stars form in various environments. SOFIA also investigates the chemical composition of the raw materials of planet formation, studies the development of complex hydrocarbons, and explores the far-reaching implications for understanding our place in the universe.

SOFIA surveys the interstellar medium, which contains an elemental record of the generations of stars that have lived and died since the galaxy's birth. SOFIA's instruments are well suited for spectral imaging of bright sources and extended regions of the Milky Way and nearby galaxies. These data are used to probe the physics and chemistry of a variety of environments and conditions. SOFIA explores how stars interact with their environments, the origin of dust, and the role of complex molecules.

SOFIA studies the Milky Way and other galaxies, investigating the many questions that arise in these complex environments. The observations provide critical information about the interactions of stars, powerful gas flows and stellar winds, strong magnetic fields, and supermassive black holes. Because of the extreme visual extinction to the galactic center, its abundant energy emerges almost entirely in the infrared, and is well suited for study by SOFIA.

Although magnetic fields are notoriously difficult to observe, polarimetric observations of the infrared emission from aligned dust grains has proven to be a powerful technique. SOFIA maps polarized light that results from the effect magnetic fields have on dust in and around celestial objects, allowing astronomers to learn how magnetic fields affect the birth of stars, the dynamics of the galactic center, and even the extreme environment of active galactic nuclei.

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

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.

## SCIENCE INSTRUMENT ACRONYMS

EXES: Echelon-cross-Echelle Spectrograph

FORCAST: Faint Object InfraRed Camera for the SOFIA Telescope

FIFI-LS: Field-Imaging Far-Infrared Line Spectrometer

GREAT: German Receiver for Astronomy at Terahertz Frequencies

HAWC+: High-resolution Airborne Wideband Camera

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## CREDITS

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Front cover image: NASA/Carla Thomas

Back cover image: NASA/Tom Tschida

# Magnetic Structure of Messier 82

Composite image of Messier 82. The magnetic field detected by SOFIA, shown as streamlines, appears to follow the bipolar outflows (red) generated by the intense nuclear starburst. The image combines visible starlight (gray) and a tracing of hydrogen gas (red) from the Kitt Peak Observatory, with near-infrared and mid-infrared starlight and dust (yellow) from SOFIA and the Spitzer Space Telescope. (NASA/SOFIA/E. Lopez-Rodriguez; NASA/Spitzer/J. Moustakas et al.)

Observations of Messier 82, 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.

HAWC+ polarization of the far-infrared emission from dust grains provides a powerful technique to map the magnetic fields in the Milky Way and other galaxies. To build a complete view of dust emission, HAWC+ observed at 53  $\mu\text{m}$ , which samples the warmer dust in the interior of Messier 82, and 154  $\mu\text{m}$ , which favors the cooler dust surrounding the central regions. The data reveal a magnetic field geometry perpendicular to the plane of the galaxy, extending at least 700 parsecs along the disk, with a transition to a more planar field further away from the galaxy center. The galactic wind also transports a huge amount of gas and dust — the equivalent of 50 million Suns.

These observations indicate that the powerful winds associated with the starburst phenomenon could be one of the mechanisms responsible for seeding material and injecting a magnetic field into the nearby intergalactic medium. If similar processes took place in the early universe, they would have affected the fundamental evolution of the first galaxies.

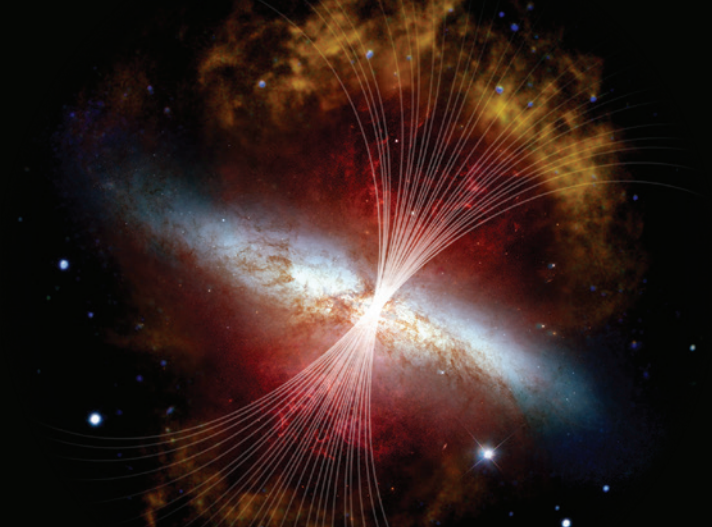
**Paper: Jones et al., 2019, ApJL, 870, L9.**

Do the magnetic field lines of Messier 82 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?

A well-tested technique used in heliophysics — the potential field extrapolation — was used to determine, for the first time, if the field lines of Messier 82 are *open* or *closed*. Analysis shows that the turbulent kinetic and magnetic energies are in close equipartition at 10 kpc from the center of the galaxy. 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 Messier 82 are *open*.

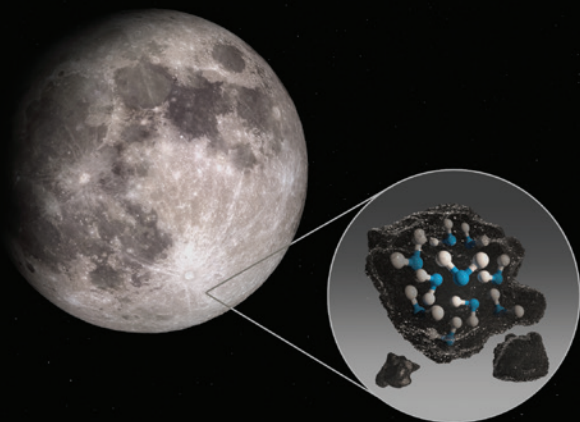
Magnetic fields generated by turbulent gas motions arising from galactic outflows, mergers, and active galaxies may permeate the intergalactic medium. The powerful winds associated with the starburst phenomenon appear to be responsible for injecting material enriched with elements like carbon and oxygen into the intergalactic medium. These discoveries help explain how matter and magnetic fields escaped their host galaxies and began to fill the surrounding voids.

**Paper: Lopez-Rodriguez et al., 2021/06, ApJ, 914, 24.**



Magnetic fields lines in Messier 82 overlaid on a visible and infrared composite image 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). (NASA, SOFIA, L. Proudfit; NASA, ESA, Hubble Heritage Team; NASA, JPL-Caltech, C. Engelbracht)

# Fundamental Spectroscopic Discoveries



*This illustration highlights the Moon's Clavius Crater in the southern hemisphere, where traces of water were detected by SOFIA. The callout depicts water molecules trapped inside tiny, glass bead-like structures within the lunar soil. These structures may prevent water from being lost to space, allowing it to remain on the harsh, nearly airless lunar surface. (NASA/Ames Research Center/Daniel Rutter)*

**R**esearchers using SOFIA have made the first-ever detection of the water molecule on the sunlit surface of the Moon. This discovery refines our understanding of the behavior of water and how volatile elements and compounds interact with airless bodies throughout the solar system and beyond. Water and other volatiles can influence the internal processes and surface expression of planets. Water suppresses the melting point of rock, promoting volcanism, and reduces the viscosity of planetary interiors, enabling more efficient internal circulation and heat transfer.

The unambiguous water detection was made possible by SOFIA's unique capabilities and the sensitivity of the FORCAST spectrometer. The fundamental bending vibration of the H-O-H molecular bond occurs at  $6.1 \mu\text{m}$  in the infrared. This region of the spectrum is completely obscured from the ground by water in the Earth's atmosphere, but is highly transparent from SOFIA's operational altitude in the stratosphere. In addition, the spectral feature at  $6.1 \mu\text{m}$  is unique to water and does not suffer from blending from other OH-related compounds.

Further observations with SOFIA covering large areas obtained at various times of the lunar day will enable scientists to learn about the storage, retention, and migration of water. These studies are critical for future NASA missions, including VIPER, a lunar rover that will explore the landscape near the Moon's South Pole, and the Artemis program that will return humans to the Moon.

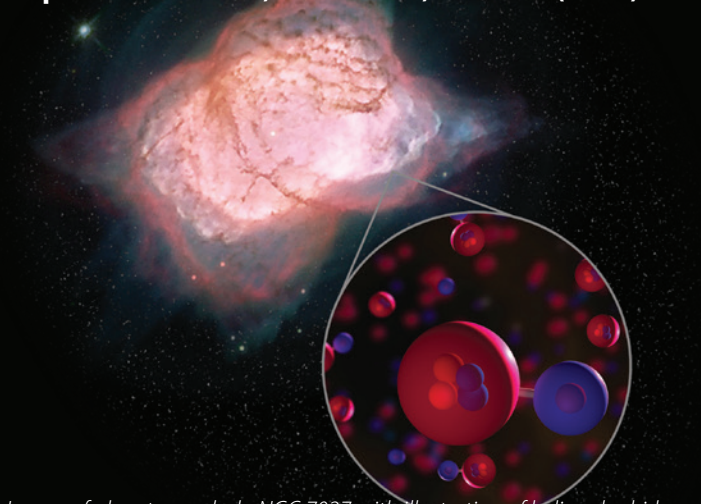
**Paper: Honniball et al., 2021, Nature Astronomy, 5, 121.**

**S**OFIA detected the first type of molecule that ever formed in the universe, helium hydride. When the universe was still very young, only a few kinds of atoms existed. Scientists believe that around 100,000 years after the big bang, helium and hydrogen combined to make the first molecule. Helium hydride has been predicted by chemical models and created in the laboratory, but decades-long searches for this elusive molecule in an astrophysical environment have been unsuccessful — until now.

The GREAT instrument detected modern helium hydride in a planetary nebula, NGC 7027, located 3,000 light-years away near the constellation Cygnus. The radiation field produced by the central white dwarf star combined with a high density of hydrogen and helium provided the conditions where helium hydride could form in the modern universe.

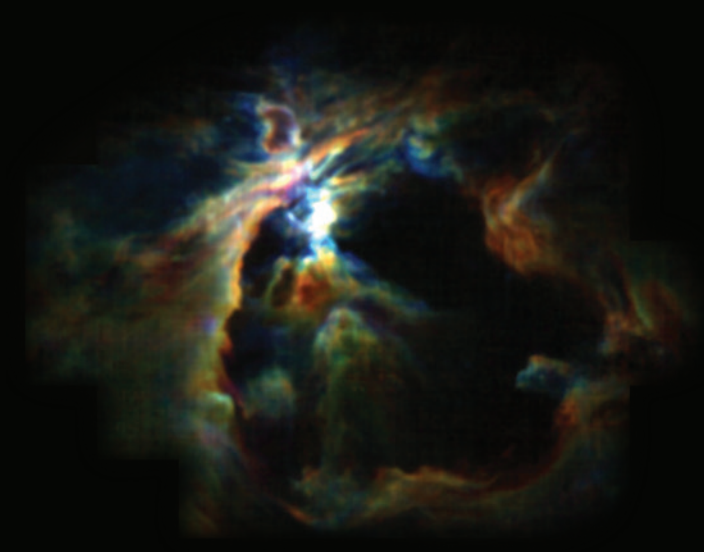
Understanding how primordial gas evolves into the galaxies, stars, and planets we see today remains one of the most important goals of modern astrophysics. When temperatures in the early universe fell below  $\sim 4,000 \text{ K}$ , the light elements produced in the big bang began to combine. Ionized hydrogen interacting with neutral helium created the universe's first molecular bond. Destruction of this bond provided a pathway to the formation of molecular hydrogen, the most abundant and significant molecule in the universe. The growing abundance of such molecules influenced the structure of the early universe by providing a dominant mechanism for gas to cool and form stars.

**Paper: Güsten et al., Nature 568, 357–359 (2019).**



*Image of planetary nebula NGC 7027 with illustration of helium hydride molecules. In this planetary nebula, SOFIA detected helium hydride, a combination of helium (red) and hydrogen (blue), which was the first type of molecule to ever form in the early universe. This is the first time helium hydride has been found in the modern universe. (NASA/ESA/Hubble Processing: Judy Schmidt)*

# Star Formation Triggered by Stellar Winds



[CII] emission from SOFIA shows the powerful wind from the newly formed star at the heart of the Orion Nebula is creating the bubble (black) and preventing new stars from forming in its neighborhood. At the same time, the wind is pushing molecular gas (color) to the edges, creating a dense shell around the bubble where future generations of stars can form. (NASA/SOFIA/Pabst et al.)

**T**he stellar wind from a newborn star in the Trapezium of the Orion Nebula forms a bubble and disrupts star birth in its neighborhood. At the same time, it pushes molecular gas to the edges of the bubble, creating new regions of dense material where future stars might form. These feedback effects regulate the physical conditions of the nebula, influence the star formation activity, and ultimately drive the evolution of the interstellar medium.

The GREAT instrument on SOFIA recorded over 2 million [CII] spectra in only 40 hours. The observations provide new insights into the kinematics and dynamics of the shell surrounding the bubble of material blown out by the strong stellar wind. The 3D view provided by the observations also reveals a rich structure of the nebula, including filaments, colliding flows, and a completely distinct view of the molecular gas distribution.

The interaction of massive stars with their surrounding environments regulates the evolution of star formation. Energy from these massive stars stirs up the medium, heats the gas, and disrupts the birth sites of new stars. Until now, it was generally thought that supernova explosions were the dominating factor controlling the environment of star-forming clouds, but these results from SOFIA show that the stellar wind interactions dominate feedback at a much earlier phase in the cloud's star-producing lifetime.

**Paper: Pabst et al., 2019/01, Nature, 565, 618.**

**S**OFIA observations show that the high-mass star-forming region RCW 120 is expanding rapidly, causing molecular material at the outskirts of the region to pile up. The resulting compression can lead to the formation of new stars — a process known as positive stellar feedback. Although feedback has been studied in a variety of environments, these new observations demonstrate for the first time that it can operate on short timescales, potentially shedding light on the star formation history of the universe.

The [CII] observations of RCW 120 reveal that the region is rapidly expanding toward us with a velocity of ~15 km/s. Given the physical size of RCW 120, this suggests that the region is only ~150,000 years old, much younger than previously thought. The energetics indicate that the stellar wind is indeed the main driver of the expansion, because other effects like photoionization cannot provide the necessary energy. Since there is ongoing triggered star formation around RCW 120, the observations imply that the feedback process is extremely rapid.

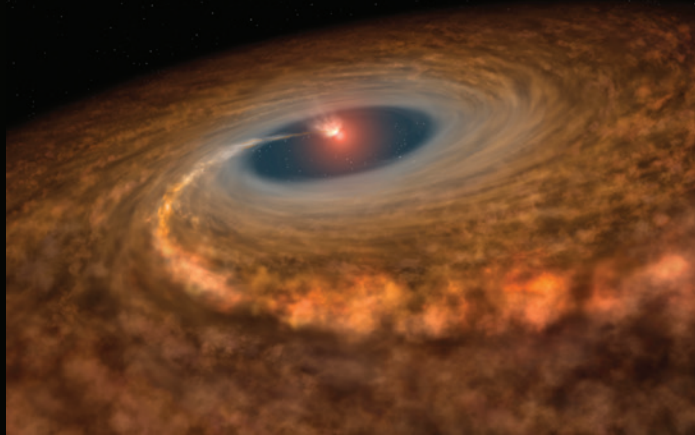
If this result is representative for star-forming regions, they may have major ramifications for the study of galaxy evolution in the early universe. Stars back then are expected to have been massive, and they therefore would have produced strong feedback effects. Rapid triggered star formation around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

**Paper: Luisi et al., 2021/04, SciA, 7, 9511.**



Composite image of the nebula RCW 120. The ring-shaped clouds around the nebula were detected by the Spitzer Space Telescope. SOFIA measured the glowing gas shown in red and blue to study the nebula's expansion speed and determine its age. The blue gas represents gas expanding in the direction toward Earth and the red away from Earth. (NASA/JPL-Caltech/SOFIA)

# Episodic Accretion in High-Mass Protostars



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)

**T**heory 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.

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 otherwise hard to discover. 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 FIFI-LS instrument on SOFIA. The comparison of pre-burst and burst spectral energy distributions confirmed the 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.

**Paper: Stecklum et al., 2021/02, A&A, 646A, A161.**

**E**pisodic accretion may be one of the most important processes in the later stages of star formation, accounting for about 25% of a star's final mass. While these events are observationally well established in low-mass stars, comparatively little is known about the formative years of massive stars. While monitoring NGC 6334 I, a well-studied proto-cluster, researchers discovered a millimeter outburst from a massive protostar that was so deeply embedded that it was unobservable in the infrared prior to the outburst.

New observations by FORCAST and HAWC+ revealed that the protostar was now the brightest infrared source in the entire proto-cluster. Radiative transfer models were used to determine an outburst luminosity of almost 50,000 Suns, 16 times higher than the pre-outburst value. The NGC 6334 I outburst now exceeds all other outbursts by a factor of about three in both duration and energy output.

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.

**Paper: Hunter et al., 2021/05, ApJL, 912, L17.**



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

# Magnetically Regulated Star Formation



Composite image of the Serpens South Cluster. Magnetic fields observed by SOFIA are shown as streamlines over an image from the Spitzer Space Telescope. SOFIA results indicate that gravity can overcome some of the strong magnetic fields to deliver material needed for new stars. (NASA/SOFIA/T. Pillai; NASA/JPL-Caltech/L. Allen)

The vast space between stars is home to filamentary gas and dust features that appear to play a major role in channeling mass into young clusters where stars can form. These formation processes are driven by a complex interplay of several fundamental forces including turbulence, gravity, and the magnetic field. In order to get an accurate description for how dense clusters of stars form, astronomers need to pin down their relative roles.

Studies done with Planck data found that the orientation of the magnetic field is parallel to the filaments in low-density environments and perpendicular in high-density environments. But in order for stars to form, these filaments must lose their magnetic fields. When and where does this happen? HAWC+ observations were obtained to study the role of magnetic fields in the Serpens South Cluster, a young, nearby star-forming region that sits at the center of a network of dense filaments.

The finer resolution of HAWC+ revealed a twist to the Planck story. In the most opaque parts of certain filaments, the observations show that the magnetic field is once again aligned. This transition appears to result as the magnetic field succumbs to the strength of the gas flow, allowing gravitational collapse and cluster formation to occur even in the presence of relatively strong magnetic fields. Additional observations and modeling will be needed to understand the forces that govern the complex processes of star formation.

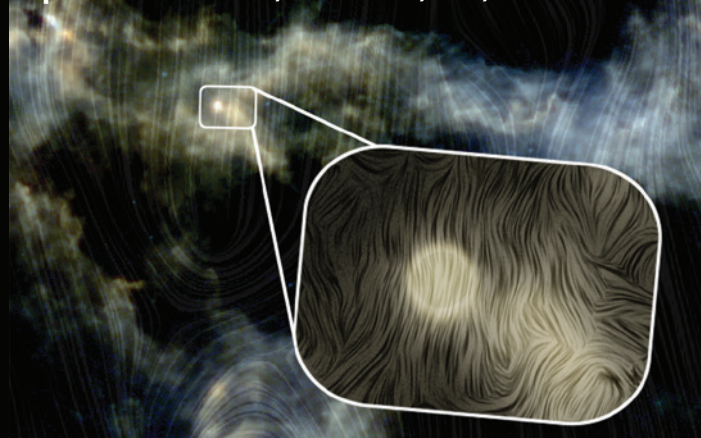
**Paper: Pillai et al., 2020/08, Nature Astronomy, 4, 1195.**

SOFIA studied the initial stages of star formation in a highly magnetized environment. HAWC+ targeted the low-mass protostellar core, IRAS 15398-3359, which hosts a protostar younger than 10,000 years. It is embedded in the Lupus I molecular cloud, the least evolved component of the Lupus complex. Previous optical polarimetry of this cloud, which traces the low-density cloud-scale magnetic field, revealed a uniform strength of  $B \approx 100 \mu\text{G}$  and a field structure aligned perpendicular to the main axis of the cloud.

The optical and far-infrared polarization vectors both trace a common direction indicating that the core preserved the magnetic field morphology inherited by the parental cloud while it was evolving and contracting. The far-infrared data close to the central protostar reveal a uniform field that is roughly aligned with the outflow direction, as predicted by the theory of magnetically-driven collapse. However, on the south-east side of the core, the field lines pinch inward, unveiling a (partial) hourglass shape. If confirmed by further, deeper observations, this would represent the first hourglass shape detected by SOFIA in the low-mass regime.

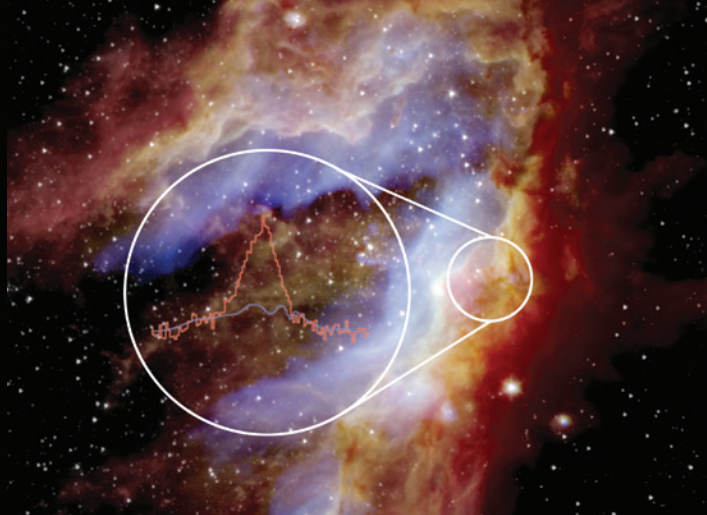
Results also indicate a gravitational-to-magnetic energy ratio just below unity, likely arising from an average between the core, where gravity dominates, and the outskirts. The SOFIA results indicate that IRAS 15398-3359 evolved in a highly magnetized environment and that the ordered magnetic field was preserved from cloud scales down to core scales.

**Paper: Redaelli et al., 2019 A&A, 631, A154.**



A portion of the Lupus I cloud complex. Color shows the emission by interstellar dust grains at three different wavelengths observed by Herschel (250, 350, and 500  $\mu\text{m}$ ). Streamlines show the associated magnetic fields based on Planck polarization data. The inset shows a HAWC+ total intensity image and polarization streamlines of the low-mass protostellar core, IRAS 15398-3359. (Background: ESA/Herschel/Planck; J. D. Soler, MPIA; Inset: Redaelli et al., 2019.)

# Optical Depth Complexities of [CII]



Average spectra of the [CII] emission for M17 SW superposed on a composite image with Herschel (70  $\mu\text{m}$ , red), Spitzer (3.6  $\mu\text{m}$ , white), and SOFIA (37  $\mu\text{m}$ , green)-data. Compare the [ $^{12}\text{CII}$ ] spectrum (blue) with the [ $^{13}\text{CII}$ ] spectrum (red), which has been scaled up (by the  $^{12}\text{C}/^{13}\text{C}$  abundance ratio of 40 and the relative satellite weight of 1/0.25). (M17 SW: NASA/SOFIA/De Buizer/Radomski/Lim; NASA/JPL-Caltech; ESA/Herschel; Inset: C. Guevara et al.)

**T**he cosmic cycle of star formation is an essential part of the evolution of the universe. The ultraviolet radiation from massive stars creates warm layers on the surface of the surrounding molecular clouds. It dominates the thermal balance, chemistry, structure, as well as the distribution of the gas and dust. The radiation dissociates molecules, ionizes atoms, and heats the gas and dust. The carbon line [CII] at 158  $\mu\text{m}$  is one of the important tracers of star-forming activity where the energy balance is maintained by cooling the gas through emission lines like [CII].

Traditionally, [CII] has been assumed to be optically thin, with systematic measurements done only in the last few years. GREAT observed [ $^{12}\text{CII}$ ] and its isotope [ $^{13}\text{CII}$ ] in four different regions with a wide range of physical conditions: M43, Horsehead, Monoceros R2, and M17 SW. The results indicate that the optical depth of the [ $^{12}\text{CII}$ ] line ranges from two to seven. In addition, some positions are heavily self-absorbed, with spectral dips that mimic velocity components.

The analysis shows that the origin of the [CII] emission is more complex than simple models might suggest. The structured line profiles and high optical depth visible in the bright sources of strong [CII] emission in the Milky Way revealed substantially higher [CII] column densities than those estimated using an optically thin approximation. Any physical parameters derived without accounting for the optical depth of the [CII] line should also be treated with caution.

**Paper: Guevara et al., 2020/04, A&A, 636A, A16.**

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

Recent SOFIA observations of [ $^{13}\text{CII}$ ] have revealed more and more cases of optically thick [ $^{12}\text{CII}$ ] emission from galactic star-forming regions. Now we have the first results from the Large Magellanic Cloud, indicating that the intensity of the [ $^{12}\text{CII}$ ] emission is lower by a factor of about two compared to that expected from the [ $^{13}\text{CII}$ ] intensity. The most likely explanation for this disagreement is that the [ $^{12}\text{CII}$ ] emission is optically thick.

The alternative explanation — that the isotopic ratio  $^{12}\text{C}/^{13}\text{C}$  is lower than reported in the literature — can be excluded for two reasons. The first is that the intensity ratio [ $^{12}\text{CII}$ ]/[ $^{13}\text{CII}$ ] varies over different velocity bins and is lowest at the peak of the line. The second is that the oxygen line at 63  $\mu\text{m}$  also indicates self-absorption at the velocity where the intensity ratio of [ $^{12}\text{CII}$ ]/[ $^{13}\text{CII}$ ] is lowest. These results provide a warning to astronomers that the optical depth effect should not be ignored when using [CII] as a star-formation tracer.

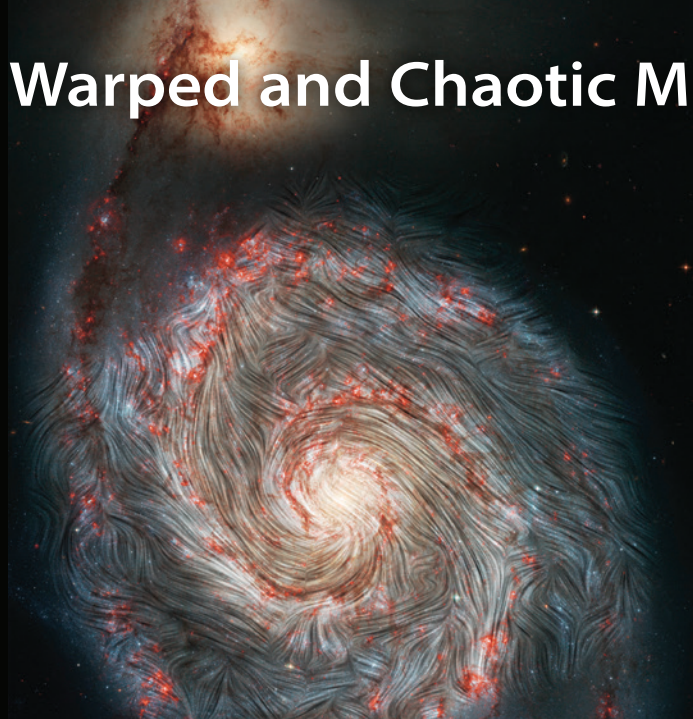
**Paper: Okada et al., 2019, A&A, 631L, 120.**



Spectrum (histogram) of [ $^{13}\text{CII}$ ] emission in the star-forming region N159W superposed on an image from Hubble Space Telescope of the Large Magellanic Cloud. The blue curve is the scaled emission that would be expected if the [ $^{12}\text{CII}$ ] emission from the same region were optically thin. The observed intensity of [ $^{13}\text{CII}$ ] is stronger than the scaled emission, indicating that [ $^{12}\text{CII}$ ] is optically thick. (NASA/SOFIA/L. Proudfit; Hubble Space Telescope)



# Warped and Chaotic Magnetic Structures



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

**M**agnetic fields appear to arise in the infant universe from inhomogeneities and anisotropies of electric charges. Theory suggests that the amplification of this “seed” field via, e.g., galaxy formation, mergers, accretion flows, and supernovae explosions as well as the feedback associated with all these processes is required to produce the fields we observe today.

HAWC+ has measured the magnetic field tracing the star-forming regions along the spiral arms of Messier 51, the Whirlpool Galaxy. The magnetic field lines in the inner region of the galaxy show a regular spiral structure, but field lines in the dense molecular material decouple from those of the diffuse gas in the outskirts. Observations show a strong distortion and large differences in their orientation with respect to the structure obtained in the radio band. This decoupling might be related to the gravitational interaction with the small companion, Messier 51b, but strikingly, this effect is not found in the inter-arm region where the gas density is much lower and many fewer stars are forming.

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

**Paper: Borlaff et al., 2021, ApJ.**

**T**he magnetic field appears to be strong enough to regulate star formation, affect the global kinematics of the gas, and even modify the rotation curve. Understanding of the origin, amplification, and morphology of the magnetic fields is crucial to forming a complete picture of galaxy development. Observations of different galaxy types are necessary to get a more comprehensive picture of how magnetic fields influence the formation and evolution of galaxies.

Centaurus A is the remnant of a merger between an elliptical and a spiral galaxy that took place about 160 million years ago. HAWC+ observations show that the magnetic field orientation is tightly aligned with the warped molecular disk. Magnetic fields were originally weak and needed to grow stronger over time, and galactic mergers appear to be one of the strengthening mechanisms. As the galactic collision triggered a burst of star formation and reshaped the original spiral galaxy, they combined with gravitational forces to distort, twist, and amplify the smaller-scale magnetic fields. Similar merging processes in the early universe may have transformed relatively weak primordial magnetic fields into the powerful forces observed today that affect how galaxies and stars are created.

SOFIA observations of relatively nearby galaxies are helping astronomers piece together a coherent picture of how the magnetic fields amplified by turbulent gas motions arising from galactic outflows, mergers, and active galaxies have evolved over cosmic time, especially during the violent, feedback-dominated early universe.

**Paper: Lopez-Rodriguez, Nat Astron (2021).**



Magnetic fields from SOFIA are shown as streamlines over a composite image of Centaurus A taken by the European Southern Observatory (ESO), Atacama Pathfinder Experiment (APEX), Chandra X-Ray observatory, and Spitzer Space Telescope. (Optical: ESO Wide Field Imager; Submillimeter: Max Planck Institute for Radio Astronomy/ESO/APEX/A. Weiss et al.; X-ray and Infrared: NASA/Chandra/R. Kraft; JPL-Caltech/J. Keene; SOFIA)

# Probing the Hot Core in Orion



Magnetic fields in the Orion Nebula, shown as streamlines over an infrared image taken by the Very Large Telescope in Chile, are regulating the formation of new stars. SOFIA's HAWC+ instrument is sensitive to the polarized emission from dust grains, which are aligned by magnetic fields. Researchers can use HAWC+ data to infer the direction and strength of these magnetic fields. (NASA/SOFIA/D. Chuss et al., ESO/M. McCaughrean et al.)

Researchers used HAWC+ observations to investigate the role of magnetic fields in the Orion Nebula, which is often used as an archetype or “Rosetta Stone” for understanding high-mass, clustered star formation throughout the galaxy. The high-resolution results enable the mapping of the field within the cores of the clouds where the later stages of the star formation process occur.

These polarimetry maps show that the magnetic field traces the “explosive outflow” emanating from the heart of the region. This explosion of material was likely caused 500–1,000 years ago by the collision of two stars after the orbital decay of a protostellar triple star system. Near the center of the explosion, the magnetic fields are overwhelmed by the energetics of the explosion; however, farther out, the kinetic energy is weaker and it appears as though the magnetic fields are guiding the ejecta. The magnetic field measurements provide valuable constraints on the energetics of this unique outflow, one of only a handful thought to result from a stellar merger.

These results for Orion are a powerful example of the utility of SOFIA/HAWC+ in understanding magnetic fields in star-forming clouds. Future results will continue to advance our understanding of the role of magnetic fields in the interstellar medium in general, and in the star formation process in particular.

**Paper: Chuss et al., 2019/02, ApJ, 872, 187.**

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. The first comprehensive high-resolution molecular line survey with EXES opens up a largely unexplored discovery space.

The hot core in Orion is a rich source of chemistry and known to harbor a variety of molecules. The HCN/HNC abundance ratio can be used as a chemical clock. Both molecules are created in similar quantities at cool temperatures, but the HNC molecule is less stable. The derived ratio from EXES is  $\text{HCN}/\text{HNC}=72$ , indicating an age of  $10^6$  years. This suggests that the hot core’s origin predates the explosive event of 500–1,000 years ago, likely caused by collision of two stars. The derived  $^{12}\text{C}/^{13}\text{C}=13$  is over five times lower than expected for Orion, 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 mid-infrared 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. The forest of molecular transitions in this wavelength region not only creates a rich legacy archive, but also provides a valuable reference database for future James Web Space Telescope observations.

**Paper: Nickerson, et al., 2021/01, ApJ, 907, 51.**

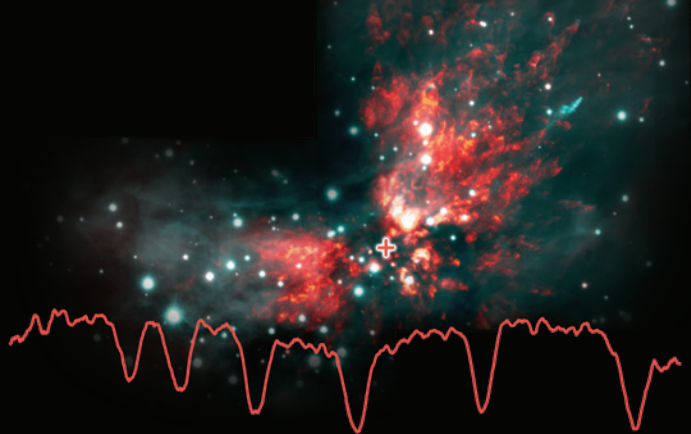


Image of the Orion KL region taken by the Gemini South Telescope with the cross marking the hot core. The  $\text{H}_2$  in red and  $[\text{FeII}]$  in blue trace finger-like tendrils resulting from the blast. The SOFIA EXES spectrum across the bottom shows multiple ro-vibrational transitions of the HNC molecule near  $21.6\ \mu\text{m}$  seen in absorption. (Orion: Bally et al. 2015; Gemini South GSAOI; Spectrum: Nickerson et al., 2021)

# Earth's Atmosphere and Oceans



Artist's depiction of a comet and its coma. (Lynette Cook)

**A** key question in astrophysics concerns the development of the conditions of habitability in planetary systems. Water is an essential ingredient for carbon-based life as we know it. However, the source of terrestrial water is still unknown. In the standard model of the protosolar nebula, the temperature in the terrestrial planet-forming zone was too high for water ice to survive. Consequently, the Earth accreted dry and the present-day water had to be delivered in a later phase, together with organics, by external sources such as comets or asteroids.

GREAT observations of water in the Jupiter-family comet Wirtanen give the same deuterium-to-hydrogen (D/H) ratio as in the Earth's oceans. A striking anti-correlation is seen between the D/H ratio in water and the active fraction, defined as the ratio of the active surface area to the total comet surface. Hyperactive comets like Wirtanen typically have D/H ratios in water consistent with the terrestrial value. These comets require an additional source of water vapor in their coma, explained by the presence of subliming icy grains expelled from the nucleus.

Enlarging the number of accurate D/H measurements in both Jupiter-family and Oort cloud comets is of paramount importance for understanding the origin of the Earth's water. Such measurements made from the ground lead to large observational uncertainties. The GREAT instrument onboard SOFIA plays a key role in this endeavor, critical for understanding planetary habitability.

**Paper: Lis et al., A&A 625, L5 (2019)**

**A**tomistic oxygen, an important player in climate change models, has been measured directly for the first time in one of the least understood regions of Earth's upper atmosphere. These results from SOFIA help solidify some of the basic science around how solar energy is exchanged between the Earth's surface and space.

The upper atmosphere is difficult to study — ground-based telescopes are hampered by distortion from water vapor, satellites can infer levels of oxygen but cannot make direct measurements, while rockets and the space shuttle offered only brief snapshots of this region. GREAT observations of the atomic oxygen line at  $63\ \mu\text{m}$  show Doppler broadening that varies with the altitude of the emission site. These atmospheric data are a by-product of astronomical observations in the same frequency band. Astronomers have always treated the atmospheric data as contamination and filtered it out from the sought-after celestial signal.

For analysis of the spectra, researchers developed a radiative transfer code based on atomic oxygen concentration and temperature profiles from a semi-empirical model and satellite measurements. The expected atomic oxygen emission was modeled and compared with the emission measured by GREAT, and the agreement was excellent, with differences within the uncertainty. A trove of atomic oxygen data obtained with GREAT already exists in the archive. These SOFIA measurements are an important step towards a conclusive understanding of the Earth's upper atmosphere and reliable confirmations of climate model predictions.

**Paper: Richter et al., Commun Earth Environ 2, 19 (2021).**



Noctilucent or "night shining" clouds forming in the mesosphere as seen from the International Space Station on May 29, 2016. These clouds form between 47 to 53 miles (76 to 85 kilometers) above Earth's surface, near the boundary of the mesosphere and thermosphere, a region known as the mesopause. (ESA/NASA/Tim Peake)



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