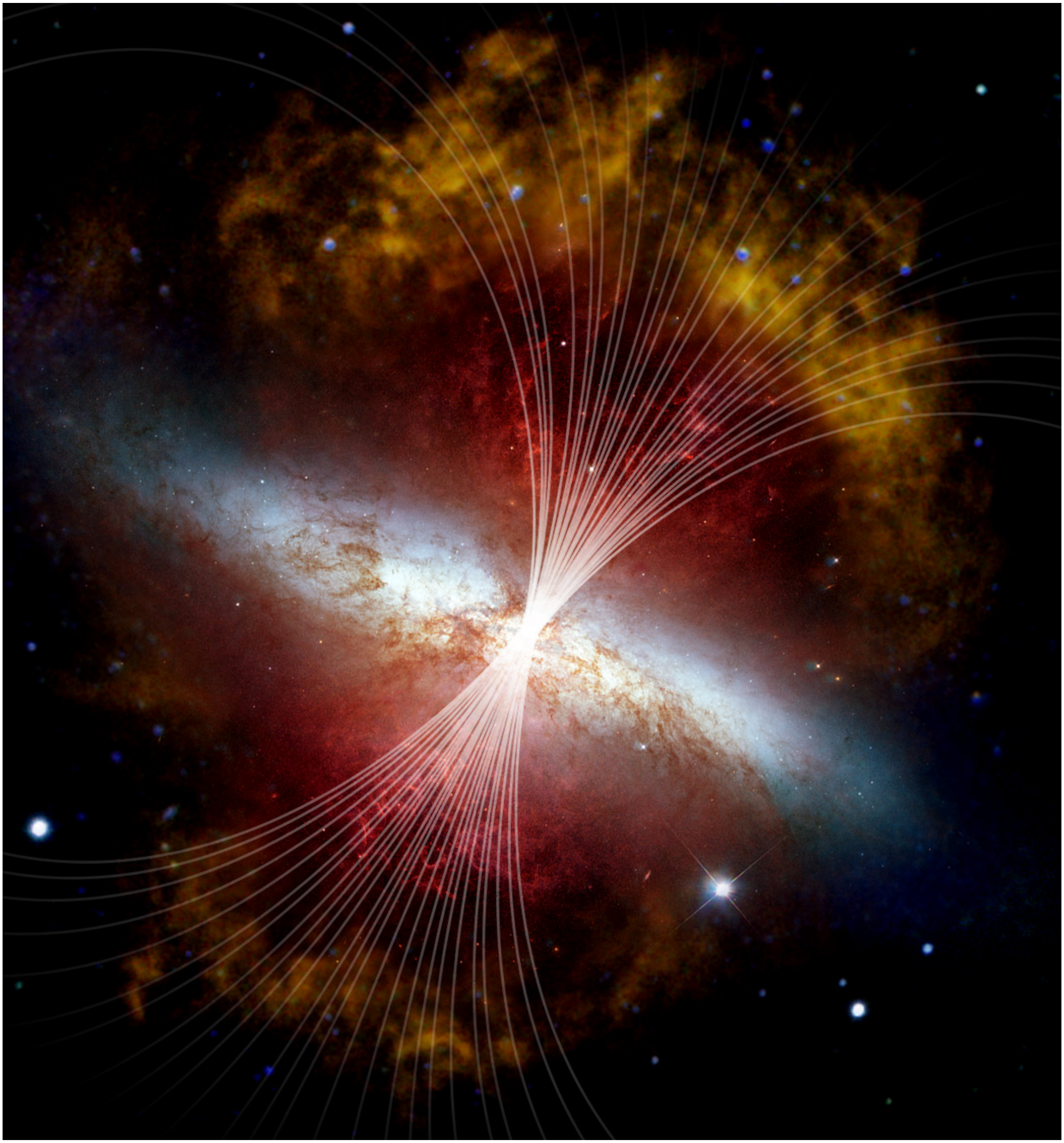
SOFIA:

Making the Magnetic Field Visible



Magnetic fields lines in Messier 82 overlaid on a visible and infrared composite image. See Science Spotlight, page 2. *(NASA, SOFIA, L. Proudfit; NASA, ESA, Hubble Heritage Team; NASA, JPL-Caltech, C. Engelbracht)*

Science Spotlight

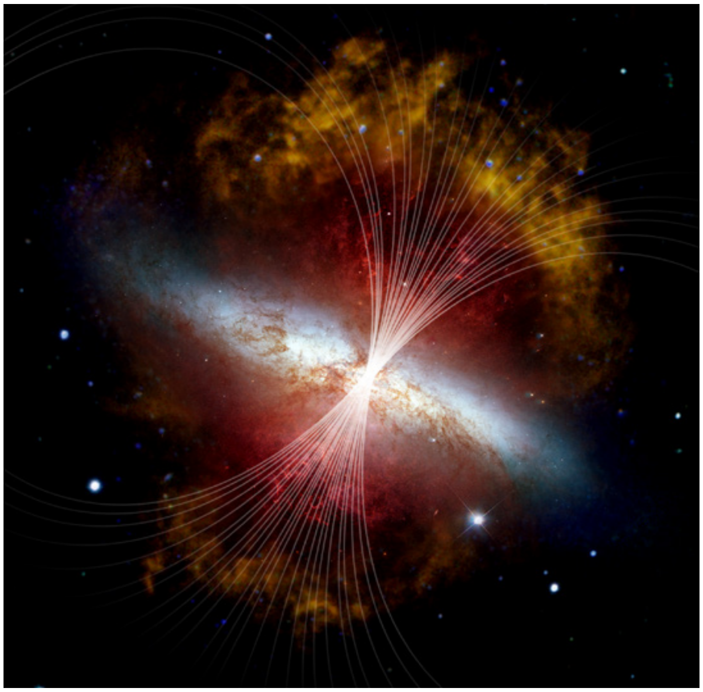
Joan Schmelz, *Universities Space Research Association*

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 the High-resolution Airborne Wideband Camera-Plus (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 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 reduces to zero at infinity and generates the measured field at the photosphere.



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). 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)*

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 setup 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,∞) = 0.

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. Schmelz
Reference: Submitted to ApJ.

(continued on page 11)

Science Spotlight

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

SOFIA Confirms Predictions of the Density Wave Theory in NGC 1068

Stratospheric Observatory for Infrared Astronomy (SOFIA) astronomers have measured, for the first time, the magnetic field tracing the star forming regions along the spiral arms of NGC 1068, the nearest grand-design spiral with an active galactic nuclei and a large-scale, almost face-on disk.

The HAWC+ instrument onboard SOFIA provides a new approach to study magnetic fields in galaxies. Far-infrared polarimetry of magnetically aligned dust grains provides measurements of the kiloparsec-scale fields in dense regions of the interstellar medium where star formation occurs.

Although magnetic fields have been measured in galaxies for several decades, these results have been limited to the radio and optical bands. In the radio bands, synchrotron polarization traces the magnetic fields “illuminated” by relativistic electrons. In the optical, starlight is extinguished by the diffuse interstellar dust. The HAWC+ observations in the far infrared add a complementary new dimension to these studies.

SOFIA researchers were able to combine these new observations with other tracers to confirm a prediction of the density wave theory. This theory predicts that stars form in the arms as gas moves into the wave and is compressed by its gravitational potential. Under this scenario, the spiral arms should look slightly different for several tracers because they appear at different phases of the wave. The spiral traces existing stars in the optical, the inter-arm diffuse medium in the radio, and ongoing star formation in the far infrared. This is the field seen by HAWC+.

Magnetic fields in NGC 1068, or M77, are shown as streamlines over a visible light and X-ray composite image of the galaxy from the Hubble Space Telescope, the Nuclear Spectroscopic Array, and the Sloan Digital Sky Survey. The magnetic fields align along the entire length of the massive spiral arms — 24,000 light years across. This implies that the gravitational forces that created the galaxy’s iconic shape are also compressing the galaxy’s magnetic field. The increased compression from both gravity and the magnetic field also helps fuel the exceptionally high rate of star birth observed in the arms. *(NASA/SOFIA; NASA/JPL-Caltech/Roma Tre Univ.)*

About this Spotlight

Paper: SOFIA/HAWC+ Traces the Magnetic Felds in NGC 1068
Authors: E. Lopez-Rodriguez, C. D. Dowell, T. J. Jones, D. A. Harper, M. Berthoud, D. Chuss, D. A. Dale, J. A. Guerra, R. T. Hamilton, L. W. Looney, J. M. Michail, R. Nikutta, G. Novak, F. P. Santos, K. Sheth, J. Siah, J. Staguhn, I. W. Stephens, K. Tassis, C. Q. Trinh, D. Ward-Thompson, M. Werner, E. J. Wollack, E. Zweibel
Reference: 2020/01, ApJ, 888, 66.

(continued on page 12)

Science Spotlight

Thushara Pillai, *Boston University*
Joan Schmelz, *Universities Space Research Association*

Magnetized Filamentary Gas Flows in Serpens South

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. Turbulent gas motions as well as the mass content of filaments (and therefore gravitation force) can be gauged with relative ease. However, the signature of the interstellar magnetic field is so weak — about 10,000 times weaker than Earth's magnetic field — that measuring the field strengths in filaments is a formidable task.

Fortunately, a small fraction of the interstellar mass is composed of dust grains that tend to align perpendicular to the direction of the magnetic field. As a result, the light emitted by these grains is polarized, and this polarization can be used to chart the magnetic field directions. Recently, the Planck satellite produced a highly sensitive all-sky map of the polarized dust emission at wavelengths smaller than 1 mm. This provided the first large-scale view of the magnetization in interstellar filamentary features and their environments.

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. The magnetic fields have been dragged into alignment with the most powerful flows, as seen in the lower left where the streamlines are following the direction of the narrow, dark filament. This is accelerating the flow of material from interstellar space into the cloud, and fueling the collapse needed to spark star formation. *(NASA/SOFIA/T. Pillai; NASA/JPL-Caltech/L. Allen)*

Studies done with Planck data found that filaments are not only highly magnetized, but they are coupled to the magnetic field in a predictable way. The orientation of the magnetic fields is parallel to the filaments in low-density environments and perpendicular in high-density environments. This result implied that magnetic fields are playing an important role in shaping filaments.

About this Spotlight

Paper: Magnetized filamentary gas flows feeding the young embedded cluster in Serpens South
Authors: T. G.S. Pillai, D. P. Clemens, S. Reissl, P. C. Myers, J. Kauffmann, E. Lopez-Rodriguez, F. O. Alves, G. A. P. Franco, J. Henshaw, K. M. Menten, F. Nakamura, D. Seifried, K. Sugitani, H. Wiesemeyer
Reference: Nature Astronomy 2020.

But this observation also points toward a problem. In order for stars to form in gaseous filaments, these filaments have to lose these magnetic fields. When and

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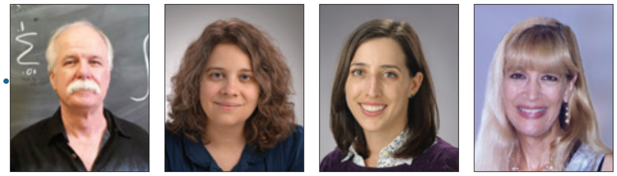


Terry Jones, *Minnesota Institute for Astrophysics*
Arielle Moullet, *Universities Space Research Association*
Kassandra Bell, *Universities Space Research Association*
Joan Schmelz, *Universities Space Research Association*

Weighing Galactic Wind Provides Clues to Evolution of Galaxies

The Cigar galaxy (M82) is famous for its extraordinary speed in making new stars, with stars being born 10-times faster than in the Milky Way. Now, data from SOFIA have been used to study this galaxy in further detail, revealing how material that affects the evolution of galaxies may get into intergalactic space.

Researchers found, for the first time, that the galactic wind flowing from the center of the Cigar galaxy is aligned along a magnetic field and transports a very large mass of gas and dust — the equivalent mass of 50 to 60 million Suns.

"The space between galaxies is not empty," said Enrique Lopez-Rodriguez, a Universities Space Research Association (USRA) scientist working on the SOFIA team. "It contains gas and dust — which are the seed materials for stars and galaxies. Now, we have a better understanding of how this matter escaped from inside galaxies over time."

Besides being a classic example of a starburst galaxy, because it is forming an extraordinary number of new stars compared with most other galaxies, M82 also has strong winds blowing gas and dust into intergalactic space. Astronomers have long theorized that these winds would also drag the galaxy's magnetic field in the same direction, but despite numerous studies, there has been no observational proof of the concept.

Composite image of the Cigar galaxy (also called M82), a starburst galaxy about 12 million light-years away in the constellation Ursa Major. 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-Rodiguez; NASA/Spitzer/J. Moustakas et al.)*

Researchers using SOFIA found definitively that the wind from the Cigar galaxy not only transports a huge amount of gas and dust into the intergalactic medium, but also drags the magnetic field so it is perpendicular to the galactic disc. In fact, the wind drags the magnetic field over more than 2,000 light-years across — close to the width of the wind itself.

"One of the main objectives of this research was to evaluate how efficiently the galactic wind can drag along the magnetic field," said Lopez-Rodriguez. "We did not expect to find the magnetic field to be aligned with the wind over such a large area."

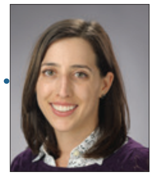
These observations indicate that the powerful winds associated with the starburst phenomenon could be one

(continued on page 12)

About this Spotlight

Paper: SOFIA Far Infrared Imaging Polarimetry of M82 and NGC 253: Exploring the Super-Galactic Wind
Authors: T. J. Jones, C. D. Dowell, E. Lopez Rodriguez, E. G. Zweibel, M. Berthoud, D. T. Chuss, P. F. Goldsmith, R. T. Hamilton, S. Hanany, D. A. Harper, A. Lazarian, L. W. Looney, J. M. Michail, M. R. Morris, G. Novak, F. P. Santos, K. Sheth, G. J. Stacey, J. Staguhn, I. W. Stephens, K. Tassis, C. Q. Trinh, C. G. Volpert, M. Werner, E. J. Wollack, and the HAWC+ Science Team
Reference: 2019, ApJL, 870, L9.

Kassandra Bell, *Universities Space Research Association*



Magnetic Field May Be Keeping Milky Way's Black Hole Quiet

Supermassive black holes exist at the center of most galaxies, and our Milky Way is no exception. But many other galaxies have highly active black holes, meaning a lot of material is falling into them, emitting high-energy radiation in this "feeding" process. The Milky Way's central black hole, on the other hand, is relatively quiet. New observations from SOFIA are helping scientists understand the differences between active and quiet black holes.

These results give unprecedented information about the strong magnetic field at the center of the Milky Way galaxy. Scientists used SOFIA's newest instrument, HAWC+, to make these measurements.

Magnetic fields are invisible forces that influence the paths of charged particles and have significant effects on the motions and evolution of matter throughout the universe. But magnetic fields cannot be imaged directly, so their role is not well understood. The HAWC+ instrument detects polarized far-infrared light, which is invisible to human eyes, emitted by celestial dust grains. These grains align perpendicular to magnetic fields. From the SOFIA results, astronomers can map the shape and infer the strength of the otherwise invisible magnetic field, helping to visualize this fundamental force of nature.

"This is one of the first instances where we can really see how magnetic fields and interstellar matter interact with each other," noted Joan Schmelz, Universities Space Research Center astrophysicist at NASA Ames Research Center in California's Silicon Valley, and a co-author on a paper describing the observations. "HAWC+ is a game-changer."

Streamlines showing magnetic fields layered over a color image of the dusty ring around the Milky Way's massive black hole. The Y-shaped structure is warm material falling toward the black hole, which is located near where the two arms of the Y intersect. The streamlines reveal that the magnetic field closely follows the shape of the dusty structure. Each of the blue arms has its own field that is totally distinct from the rest of the ring, shown in pink. *(Galactic Center dust and magnetic fields: NASA/SOFIA, star field image: NASA/Hubble Space Telescope)*

Previous observations from SOFIA show the tilted ring of gas and dust orbiting the Milky Way's black hole, which is called Sagittarius A* (pronounced "Sagittarius A-star"). But the new HAWC+ data provide a unique view of the magnetic field in this area, which appears to trace the region's history over the past 100,000 years.

(continued on page 13)

About this Spotlight

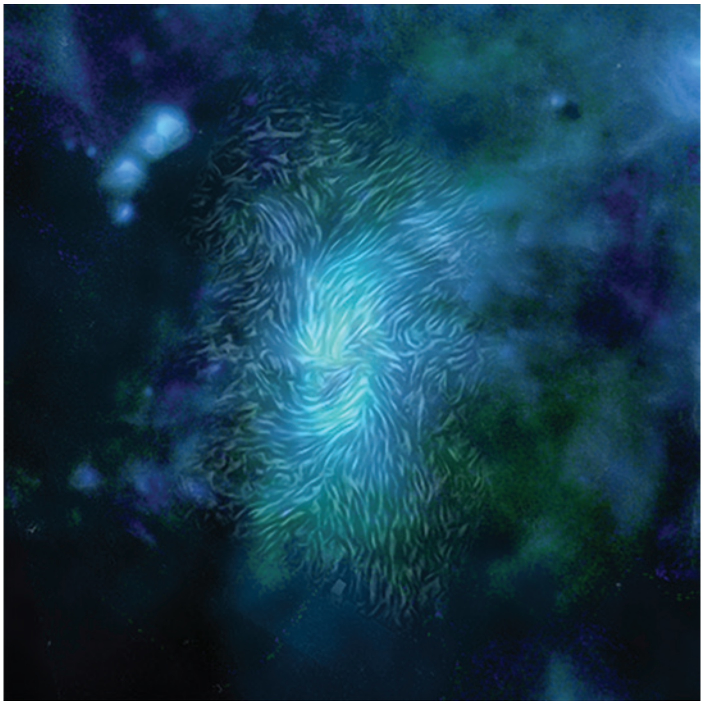
Paper: The Spiral Magnetic Field in the Central 5 Parsecs of the Galaxy
Authors: C. D. Dowell, D. T. Chuss, J. A. Guerra, M. Houde, J. M. Michail, M. Morris, J. T. Schmelz, J. Staguhn, M. W. Werner
Reference: in prep.

Science Spotlight

Joan Schmelz, *Universities Space Research Association*

The Role of the Magnetic Field in the Galactic Center

Even in a region where gravity dominates, there could be areas where magnetic fields govern the physics. The Earth's magnetosphere and the solar corona are two well-known examples. Although the gas in the central five parsecs of the Milky Way is largely neutral, the high fluxes of X-rays and cosmic rays ensure that there is sufficient residual ionization to collisionally couple the ions and neutrals. Consequently, the gas can react to the magnetic field, making the plasma beta (β) a useful indicator of the importance of the magnetic field in the environment. β is the ratio of the thermal pressure to the magnetic pressure. If the thermal pressure is greater than the magnetic pressure, then $\beta > 1$ (referred to as a high-β plasma), and the gas dynamics will control the structure of the environment. The magnetic field may be present, but it does not dominate, as is the case in the solar photosphere. If the thermal pressure is less than the magnetic pressure, then $\beta < 1$ (referred to as a low-β plasma), and the magnetic field can control the dynamics of the environment as it does in the magnetosphere and the corona.



A composite image of the central region of our Milky Way galaxy, known as Sagittarius A. SOFIA found that magnetic fields, shown as streamlines, are strong enough to control the material moving around the black hole, even in the presence of enormous gravitational forces. SOFIA's results can help answer long-standing, fundamental questions about the galactic center region: why the star formation rate is significantly lower than expected and why our galaxy's black hole is quieter than those in other galaxies. SOFIA data is shown in green (37 μm) and dark blue (25 and 53 μm). The light blue is from Herschel Space Observatory (70 μm) and the gray is from the Hubble Space Telescope. *(NASA/SOFIA/L. Proudfit; ESA/Herschel; Hubble Space Telescope)*

The HAWC+ instrument on SOFIA is providing high-quality polarization measurements for astrophysically interesting environments including the galactic center. We used these data and the Davis-Chandrasekhar-Fermi method to determine the component of the magnetic field strength in the plane of the sky. This method relates the line-of-sight velocity dispersion and the plane-of-sky polarization angle dispersion. It assumes an isotopically turbulent medium whose turbulent kinetic and turbulent magnetic energy components are in equipartition. Results indicate that B ~ 5 milliGauss, similar to the values determined for the line-of-site component of the magnetic field measured using the Zeeman Effect. Using this estimate for the magnetic field as well as values for density and temperature from the literature, we found β ~ .0001 for the overall region and β ~ .001 for sub-regions like the Western Arc and the Northern Arm.

(continued on page 13)

About this Spotlight

Paper: The Strength and Structure of the Magnetic Field in the Inner 5 Parsecs of the Galaxy
Authors: C. D. Dowell et al.
Reference: 2020, Astrophysical Journal, in prep.

David Chuss, *Villanova University*
Ralph Y. Shuping, *Space Science Institute*

Magnetic Fields in the Star Forming Clouds of Orion

One of the fundamental links in the chain of our origin story is the formation of stars and planets out of the interstellar gas and dust that exist in both our own Milky Way galaxy and in other galaxies. Stars form when these interstellar clouds of gas and dust collapse under their own gravity. However, simple gravitational collapse predicts a galactic star formation rate that is much higher than actually observed. It is thought that this inefficiency is at least partially due to magnetic fields that support the interstellar clouds against collapse; but establishing the role of magnetic fields in the star formation process has been difficult due to limitations in available instrumentation.

Luckily, magnetically aligned interstellar dust grains emit polarized light at far-infrared wavelengths. Hence, far-IR polarization can be used as a proxy for the magnetic field strength and direction in interstellar clouds. The SOFIA HAWC+ instrument is one of only a few far-IR polarimeters that astronomers can use to probe astronomical magnetic fields. The high spatial resolution provided by the 106-inch (2.7-meter) diameter SOFIA telescope and increased sensitivity over previous instruments make HAWC+ the perfect tool to address the role of magnetic fields in the star formation process.

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.)*

"HAWC+ and SOFIA have a unique and important role in the study of magnetic fields," noted Darren Dowell, the HAWC+ principal investigator at the Jet Propulsion Laboratory. "They combine the angular resolution needed to see detail in the turbulent magnetic fields and the wavelength coverage required to highlight different components of the nearby clouds."

In order to address the role of magnetic fields in star forming clouds, David Chuss from Villanova University and collaborators have obtained HAWC+ observations of the Orion Nebula, which is often used as an archetype or "Rosetta Stone" for understanding high-mass clustered star formation throughout the galaxy. The polarimetry observations have produced some of the most detailed magnetic field line maps to date, with spatial scales of ~0.01 parsecs (53µm band). Such resolution enables the

(continued on page 14)

About this Spotlight

Paper: HAWC+/SOFIA Multiwavelength Polarimetric Observations of OMC-1
Authors: D. T. Chuss, B. Andersson, J. Bally, J. L. Dotson, C. D. Dowell, J. A. Guerra, D. A. Harper, M. Houde, T. J. Jones, A. Lazarian, E. Lopez Rodriguez, J. M. Michail, M. R. Morris, G. Novak, J. Siah, J. Staguhn, J. E. Vaillancourt, C. G. Volpert, M. Werner, E. J. Wollack, D. J. Benford, M. Berthoud, E. G. Cox, R. Crutcher, D. A. Dale, L. M. Fissel, P. F. Goldsmith, R. T. Hamilton, S. Hanany, T. K. Henning, L. W. Looney, S. H. Moseley, F. P. Santos, I. Stephens, K. Tassis, C. Q. Trinh, E. Van Camp, D. Ward-Thompson, and the HAWC+ Science Team
Reference: 2019, ApJ, 872, 187.

Elena Redaelli, *Max Planck Institute for Extraterrestrial Physics*
Joan Schmelz, *Universities Space Research Association*

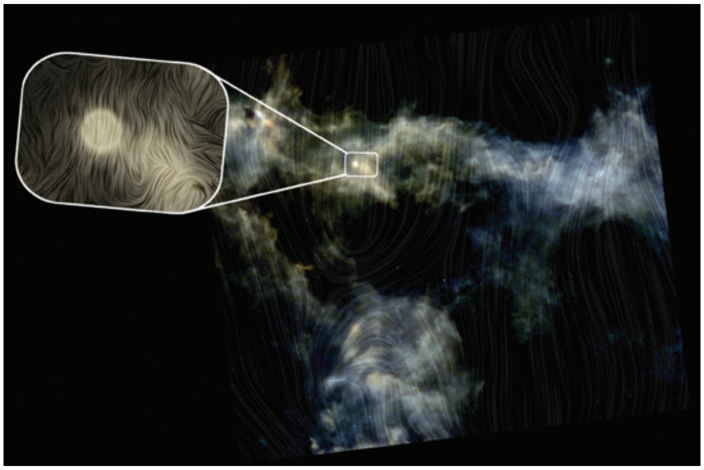
A Magnetic Hourglass Detection for a Low-Mass Protostar

Magnetic fields (B) are ubiquitous in interstellar space, and their role in the star-formation process is of fundamental importance. However, how they interplay with other important forces — such as gravity and turbulence — are topics currently under great debate. At the scales of dense cores (fractions of parsec), the theory of magnetically-driven collapse in a uniform field predicts first the formation of a flattened structure (a pseudodisc), since the matter can only flow along the field lines; later, the gravitational pull grows strong enough to pinch the field lines, giving rise to a characteristic hourglass shape. However, such a feature has been observed only rarely, especially in low-mass objects, for which there are only two clear detections reported in the literature.

Magnetic fields are difficult to detect, but the HAWC+ instrument on SOFIA observes polarized dust emission at far-infrared wavelengths that are not accessible from the ground. The dust particles are predicted to align with the local magnetic field, giving rise to thermal radiation polarized perpendicularly with respect to B.

As part of its southern deployment to New Zealand in 2018, SOFIA sought to study the initial stages of low-mass star formation in a highly magnetized environment. HAWC+ targeted the low-mass protostellar core IRAS 15398-3359, which hosts a protostar younger than 10^4 yr. 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 $B \approx 100$ μm and a field structure aligned perpendicularly to the main axis of the cloud. We obtained new polarimetric HAWC+ data at 214 μm.



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 μm). Streamlines show the associated magnetic fields based on Planck polarization data. The inset shows a HAWC+ total intensity image of the low-mass protostellar core, IRAS 15398-3359. The superposed streamlines from HAWC+ polarization data show that the magnetic fields are beginning to take on the expected hourglass shape. *(Background: ESA/Herschel/Planck; J. D. Soler, MPIA; Inset: Redaelli et al., 2019.)*

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. This is not detected on the other side, possibly due to limited sensitivity. If confirmed by further, deeper observations, this would represent the first hourglass shape detected by SOFIA in the low-mass regime.

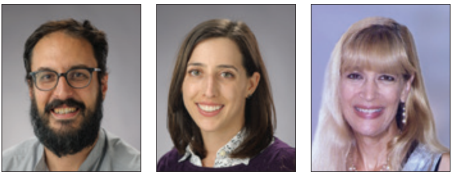
A statistical technique known as angular dispersion

(continued on page 14)

About this Spotlight

Paper: Magnetic Properties of the Protostellar Core IRAS 15398-3359
Authors: E. Redaelli, F. O. Alves, F. P. Santos, P. Caselli
Reference: 2019 A&A, 631, A154.

Science Spotlight



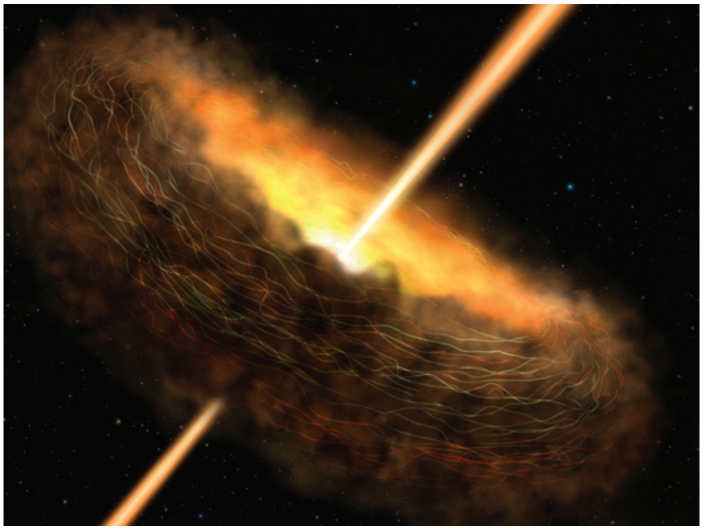
Enrique Lopez-Rodriguez, *Universities Space Research Association*
Kassandra Bell, *Universities Space Research Association*
Joan Schmelz, *Universities Space Research Association*

Magnetic Fields Confine the Torus at Cygnus A's Core

Observations from SOFIA reveal that magnetic fields are trapping and confining the obscuring dust near the center of the active galaxy Cygnus A, and feeding material onto the supermassive black hole. The unified model of active galaxies maintains that the core is surrounded by a dusty torus that absorbs radiation at all wavelengths and re-emits it in the infrared. How this obscuring structure is created and sustained has never been clear, but these new results from SOFIA confirm that the magnetic field plays a crucial role.

The presence of collimated jets that emanate from the core of active galaxies like Cygnus A implies strong accretion onto the supermassive black hole. The jets may be launched by extracting rotational energy from the black hole itself. This process requires strong magnetic fields in the nucleus of the galaxy that can help convert the rotational energy to a launching energy sufficient to overcome the enormous force of gravity near the black hole's event horizon. In fact, the fundamental difference between radio-loud galaxies like Cygnus A and their radio-quiet siblings may indeed be due to the presence or absence of a strong, coherent magnetic field surrounding the black hole.

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 recently observed the central 20 parsecs (65.2 light-years) of Cygnus A with the HAWC+ instrument at 53 and 89 µm with an angular resolution of five arcseconds and nine arcseconds. These observations are sensitive to temperatures of 30–50 K and show highly polarized infrared emission dominated by a well-aligned dusty structure. The polarization vectors indicate that the most powerful radio-loud active galaxy in the sky, with its iconic large-scale jets, is able to confine the obscuring torus that feeds the supermassive black hole using a strong magnetic field.



Artist's conception of Cygnus A, surrounded by the torus of dust and debris with jets launching from its center. Magnetic fields are illustrated trapping dust near the supermassive black hole at the galaxy's core. *(NASA/SOFIA/Lynette Cook)*

About this Spotlight

Paper: The Highly Polarized Dusty Emission Core of Cygnus A
Authors: E. Lopez-Rodriguez, R. Antonucci, R. Chary, M. Kishimoto
Reference: 2018, ApJL, 861, L23

Cygnus A is in the perfect location for observations of the role magnetic fields play in confining the tori of the unified model, channeling material into supermassive black holes, and launching jets at relativistic speeds because it is the closest and most powerful active galaxy. More observations of different types of active galaxies are necessary to get the full picture of how magnetic fields affect the evolution of the environment surrounding supermassive black holes. If, for example, a HAWC+ survey reveals highly polarized infrared emission from the centers of radio-loud active galaxies but not from radio-quiet galaxies, it would imply that magnetic fields play a crucial role in the accretion process and jet formation. ■

Magnetic Highway: Channeling the M82 Superwind

(continued from page 2)

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 2.

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.

> ***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.***

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. ■

SOFIA Confirms Predictions of the Density Wave Theory in NGC 1068

(continued from page 3)

Magnetic fields are present at all spatial scales and in all astrophysical sources observed to date in the nearby universe. Astronomers now understand that magnetic fields play a crucial role in the star formation and general dynamics of the Milky Way. These magnetic fields are strong enough to influence the distribution and structure of the gas across the interstellar medium. Thus, the characterization of observations like those from HAWC+ allows astronomers to study how magnetic fields affect and influence different astrophysical environments.

However, the role of magnetic fields in other galaxies is not well understood. Further multi-wavelength observations of different galaxy types are necessary to get a more comprehensive picture of how magnetic fields influence the formation and evolution of galaxies. Together with other observatories, SOFIA/HAWC+ can provide this empirical picture. ■

Magnetized Filamentary Gas Flows in Serpens South

(continued from page 4)

where does this happen? With an order of magnitude higher angular resolution than Planck, the HAWC+ instrument, a polarization-sensitive detector onboard SOFIA, is now able to resolve the regions where the filamentary magnetic field becomes less important.

HAWC+ observations were obtained to study the role of magnetic fields in Serpens South Cluster, a young, nearby star forming region that sits at the center of a network of dense filaments. HAWC+ confirmed the trend seen in the lower resolution — that the magnetic field is parallel to low-density gaseous filaments and perpendicular at higher densities.

The finer resolution of HAWC+, however, also 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 magneto-hydrodynamic forces that govern the complex processes involved in star formation. ■

Weighing Galactic Wind Provides Clues to Evolution of Galaxies

(continued from page 5)

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.

SOFIA's newest instrument, HAWC+, uses far-infrared light to observe celestial dust grains, which align along magnetic field lines. From these results, astronomers can infer the shape and direction of the otherwise invisible magnetic field. Far-infrared light provides key information about magnetic fields because the signal is clean and not contaminated by emission from other physical mechanisms, such as scattered visible light.

"Studying intergalactic magnetic fields — and learning how they evolve — is key to understanding how galaxies evolved over the history of the universe," said Terry Jones, professor emeritus at the University of Minnesota, in Minneapolis, and lead researcher for this study. "With SOFIA's HAWC+ instrument, we now have a new perspective on these magnetic fields."

The HAWC+ instrument was developed and delivered to NASA by a multi-institution team led by the Jet Propulsion Laboratory (JPL). JPL scientist and HAWC+ Principal Investigator Darren Dowell, along with JPL scientist Paul Goldsmith, were part of the research team using HAWC+ to study the Cigar galaxy. ■

Magnetic Field May Be Keeping Milky Way's Black Hole Quiet

(continued from page 6)

Details of these SOFIA magnetic field observations were presented at the June 2019 meeting of the American Astronomical Society and will be submitted to the *Astrophysical Journal*.

The gravity of the black hole dominates the dynamics of the center of the Milky Way, but the role of the magnetic field has been a mystery. The new observations with HAWC+ reveal that the magnetic field is strong enough to constrain the turbulent motions of gas. If the magnetic field channels the gas so it flows into the black hole itself, the black hole is active, because it is eating a lot of gas. However, if the magnetic field channels the gas so it flows into an orbit around the black hole, then the black hole is quiet because it's not ingesting any gas that would otherwise eventually form new stars.

Researchers combined mid- and far-infrared images from SOFIA's cameras with new streamlines that visualize the direction of the magnetic field. The blue Y-shaped structure (see figure, page 5) is warm material falling toward the black hole, which is located near where the two arms of the Y-shape intersect. Layering the structure of the magnetic field over the image reveals that the magnetic field follows the shape of the dusty structure. Each of the blue arms has its own field component that is totally distinct from the rest of the ring, shown in pink. But there are also places where the field veers away from the main dust structures, such as the top and bottom endpoints of the ring.

> ***This [result] could explain why our black hole is quiet while others are active.***

"The spiral shape of the magnetic field channels the gas into an orbit around the black hole," said Darren Dowell, a scientist at NASA's Jet Propulsion Laboratory, principal investigator for the HAWC+ instrument, and lead author of the study. "This could explain why our black hole is quiet while others are active."

The new SOFIA and HAWC+ observations help determine how material in the extreme environment of a supermassive black hole interacts with it, including addressing a longstanding question of why the central black hole in the Milky Way is relatively faint while those in other galaxies are so bright. ■

The Role of the Magnetic Field in the Galactic Center

(continued from page 7)

This is clearly in the low-beta regime, but observations tell us that turbulence is important in this region, and the traditional plasma beta does not account for this. Defining β' as the ratio of the turbulent-to-magnetic pressure and using a velocity dispersion from the literature, we find $\beta' \sim 0.03$. This too is in the low-beta regime, indicating that the magnetic field is capable of channeling the matter. So even though gravity dominates in the galactic center, there appear to be regions near the central black hole where the physics may be governed by the magnetic field.

These results have implications for two long-standing mysteries about the galactic center region. The first is about star formation. Even though there is an abundance of raw material, the amount of star formation is significantly less than expected. The second is about activity. Black holes at the centers of many galaxies are active, but ours is relatively quiet. A strong magnetic field could solve both these mysteries. It could suppress star formation, and it could keep the black hole from swallowing the matter it needs to form jets.

Future work will include updating the Davis-Chandrasekhar-Fermi method to work in the high-shear regions near the massive black hole. Detailed magneto-hydrodynamic modelling will also be required to explore the interplay between the magnetic field, the tidal stresses, and the turbulent motions of the gas in this extreme environment. ■

Magnetic Fields in the Star Forming Clouds of Orion

(continued from page 8)

mapping of the field within the cores of the clouds where the later stages of the star formation process occurs. These observations confirm previous results showing that magnetic fields *do* in fact help regulate the star formation process in dense interstellar clouds.

The high-resolution polarimetry maps have produced two additional interesting results. The first pertains to the process by which the dust grains become aligned. The grain-alignment mechanism is the subject of great interest both because it provides the basis for the measurements of magnetic fields and because it provides key, testable insights into the physics of the dust and its environs. The current leading theory posits that anisotropic radiation fields are an important ingredient for the alignment of the grains with the magnetic field. In other clouds, it has been observed that grain alignment efficiency degrades in the cores of clouds, presumably where the grains are shielded from the interstellar radiation field. However, in Orion Molecular Cloud 1 (OMC-1), these results show no evidence that the efficiency of this alignment process falls off in dense regions. This is likely due to the nature of the strong radiation field present within the OMC-1 clouds, presumably due to the young stars themselves.

A second result is that the magnetic field traces the "explosive outflow" emanating from the heart of the OMC-1. This explosion of material was likely caused 500–1,000 years ago by an interaction of several stars after the orbital decay of a protostellar star system.

"Explosive outflows indicate violent interactions which may terminate accretion, set stellar masses, and help establish the initial mass function," explains Professor John Bally of the University of Colorado at Boulder and a co-investigator on the HAWC+ OMC-1 observations. "Explosive outflows, in conjunction with runaway stars, demonstrate that dynamical interactions in such groups are an important ingredient in star formation."

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 that the magnetic fields are guiding the ejecta. The magnetic field measurements provide valuable constraints on the energetics of this unique outflow.

These results for Orion are powerful examples 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.

"It has been thrilling to have a front row seat to the teamwork needed to accomplish these observations," added Dowell. "I look forward to discovering whether Orion is the exception or the rule in other galactic clouds." ■

A Magnetic Hourglass Detection for a Low-Mass Protostar

(continued from page 9)

function analysis was used to determine the ratio of the turbulent (B_t) to uniform (B_0) field. The result, $B_t/B_0 = 0.267 \pm 0.007$, confirms that the uniform component dominates. We can also derive the plane-of-sky projection of the field strength, $B_{POS} = 78\ \mu G$. We also computed the gravitational-to-magnetic energy ratio, $\lambda = 0.95$. This is close to the energy balance regime ($\lambda = 1$), most likely arising from an average between the innermost part of the core, where gravity has already taken over leading to the protostar formation ($\lambda > 1.0$), and the outskirt medium, which could be still in a subcritical state ($\lambda < 1.0$).

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. For the future, we plan to analyze spectroscopic observations already collected with the Atacama Pathfinder EXperiment (APEX) in order to derive the kinematic properties of the source. These data will help us answer key questions focusing on the interaction between the magnetic field structure and the gas dynamics. ■

Starry Night with SOFIA, inspired by a comment made during the final summary of the "Ground-based thermal infrared astronomy — past, present and future" conference hosted by European Southern Observatory in October 2020.

SOFIA is a Boeing 747SP jetliner modified to carry a 106-inch diameter telescope. It is a joint project of NASA and the German Aerospace Center, DLR. 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 (DSI) at the University of Stuttgart. The aircraft is maintained and operated from NASA's Armstrong Flight Research Center, Building 703, in Palmdale, California.

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