THE SPIRAL MAGNETIC FIELD OF NGC1068

ENRIQUE LOPEZ-RODRIGUEZ
Scientist at the Stratospheric Observatory for Infrared Astronomy (SOFIA)
NASA Ames Research Center, Moffett Field, CA

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Collaborators:

Dowell, C. D. (JPL)
Harper, D. A. (UofChicago)
Jones, T. J. (UofMinnesota)
Berthoud, M. (UofChicago)
Chuss, D. (Villanova U.)
Dale, D. A. (UofWyoming)
Guerra, J. A. (Villanova U.)
Hamilton, R. (Lowell Observatory)
Looney, L. W. (UofIllinois)
Michail, J. M. (Northwestern U.)
Nikutta, R. (NOAO)
Novak, G. (Northwestern U.)
Santos, F. P. (Max Planck Institute)
Sheth, K. (NASA)
Siah, J. (Villanova U.)
Staguhn, J. (NASA)
Tassis, K. (UofCrete)
Trinh, C. (SOFIA)
Ward-Thompson, D. (UofCentralLansashire)
Werner, M. (JPL)
Wollack, E. J. (NASA)
Zweibel, E. G. (UofWisconsin)
and
HAWC+ Science Team
ROLE OF MAGNETIC FIELDS IN GALAXIES

Main goal: Study the role of magnetic fields in the interstellar medium of nearby galaxies

Magnetic fields play important roles in:
- dynamical evolution of the interstellar medium of galaxies,
- processes governing formation of stars, and
- dynamical evolution of galaxies.

What is the geometry of these large-scale magnetic fields?
What are the dominant physical mechanisms of these large-scale magnetic fields?
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IR-submm polarimetry has shown to be a powerful tool to study B-fields.
MAGNETIC FIELDS INFERRED BY POLARIMETRIC TECHNIQUES: OPTICAL-NIR

Example:
- M51 at optical shows an almost azimuthal polarization pattern with $P<2\%$ (Scarott et al. 1987)
- M51 at H-band shows $P<0.05\%$ across the host galaxy (Pavel et al. 2012)

The combination of Optical and NIR rules out a dichroic absorption polarization origin.

Optical-NIR polarimetry mainly suffers from dust/electron scattering.


Pavel & Clemens (2012)
MAGNETIC FIELDS INFERRED BY POLARIMETRIC TECHNIQUES: RADIO

In the radio wavelength, the emission arises from non-thermal physical processes.
- Radio observations at cm measure the synchrotron radiation in the diffuse ISM from relativistic electrons (sensitive to the cosmic ray electron population).
- Radio polarimetry traces the magnetic fields ‘illuminated’ by relativistic electrons.

Example:
- M51 at radio cm wavelengths shows large-scale spiral magnetic fields (Fletcher et al. 2011)
MAGNETIC FIELDS INFERRED BY POLARIMETRIC TECHNIQUES: FAR-INFRARED

Optical-NIR polarization suffer of dust/scattering polarization
Radio wavelength traces the diffuse ISM and samples the relativistic electrons.
  ‣ Faraday rotation needs to be taken into account.

FIR wavelengths:
  ‣ Sensitive to temperature (helps to separate regions along the LOS)
  ‣ Traces the total gas and dust in the dense ISM.

The influence of magnetic field in the dust at several galactic scales is investigated using FIR polarimetric observations
UNDERSTANDING POLARIZATION ARISING BY MAGNETICALLY ALIGNED DUST GRAINS

Magnetic field can induce a preferential orientation of dust grains

The PA of polarization from emission is perpendicular to the PA of polarization from extinction

***Disclaimer: dust grain alignment theory can get very complex, we can talk later about the details.***

Credit: Santos F.
POLARIMETRY: OBSERVATIONAL STRATEGY

We need:
- FIR observations to trace the polarized emission by magnetically aligned dust grains.
- High-spatial resolution observations to obtain sensitive polarimetric measurements
If dust grains are aligned, then we should measure some level of polarization and infer the B-field morphology.

Polarization enhances the observed emission in the ionization cones and core.

Ionization cone: dust scattering
Core: dichroic absorption
INSTRUMENTATION

SOFIA/HAWC+
SOFIA: 2.7-m telescope
WAVELENGTH RANGE: 0.3-300 microns
INSTRUMENTS: 7 First generation instruments: cameras, spectrometers & high-spectrometers. New instrument: imager-polarimeter at 50-200 microns (HAWC+)
AIRSPEED: Mach 0.85 (560 mph ~ 901 kmh)
OBSERVING ALTITUDE: 37,000 - 45,000 ft
ONBOARD STAFF: Flight crew 3; Mission crew 2-6, Scientist 1-3, Educators 5-15
AVERAGE SCIENCE FLIGHT LENGTH: 10 hours overnight
The SOFIA Instruments

- U.S. Principal Investigator Instrument
- U.S. Facility Instrument
- German Principal Investigator Instrument
- German Facility Instrument
- Future Capabilities

Resolving Power ($\lambda/\Delta\lambda$)

Wavelength ($\mu$m)
HAWC+: SPECIFICATIONS

The far-infrared emission, detected by HAWC+, samples different dust temperatures in the range of 10K to 100K.

<table>
<thead>
<tr>
<th>Band / Wavelength</th>
<th>$\Delta\lambda/\lambda$</th>
<th>Angular Resolution</th>
<th>Total Intensity FOV (arcmin)</th>
<th>Polarization FOV (arcmin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A / 53 $\mu$m</td>
<td>0.17</td>
<td>4.7&quot; FWHM</td>
<td>2.7 x 1.7</td>
<td>1.3 x 1.7</td>
</tr>
<tr>
<td>B$^a$ / 63 $\mu$m</td>
<td>0.15</td>
<td>5.8&quot; FWHM</td>
<td>4.2 x 2.6</td>
<td>2.1 x 2.6</td>
</tr>
<tr>
<td>C / 89 $\mu$m</td>
<td>0.19</td>
<td>7.8&quot; FWHM</td>
<td>4.2 x 2.6</td>
<td>2.1 x 2.6</td>
</tr>
<tr>
<td>D / 154 $\mu$m</td>
<td>0.22</td>
<td>14&quot; FWHM</td>
<td>7.3 x 4.5</td>
<td>3.6 x 4.5</td>
</tr>
<tr>
<td>E / 214$\mu$m</td>
<td>0.20</td>
<td>19&quot; FWHM</td>
<td>8.0 x 6.1</td>
<td>4.0 x 6.1</td>
</tr>
</tbody>
</table>

HAWC+ observes total and polarized emission of dust grains at five different wavelengths in the range of 50-250 micrometers.
SOFIA POLARIMETRIC OBSERVATIONS OF NGC 1068

THE SPIRAL MAGNETIC FIELD
PHYSICAL STRUCTURES OF NGC 1068: HOST GALAXY

- Grand-design spiral galaxy at 13.5 Mpc (1” = 65 pc)
  - Active galactic nuclei (Seyfert 2)
  - Circumnuclear starburst
PHYSICAL STRUCTURES OF NGC 1068: IONIZATION CONE & AGN

Associated with the AGN:
- Narrow line-region (ionization cone)
- ~1.3 kpc (20") at PA~40°
- North protruding toward us out of the plane of the galaxy.
PHYSICAL STRUCTURES OF NGC 1068: RADIO JET

Associated with the AGN:

- Jet:
  - N-S at pc-scales
  - \sim 45^\circ at 100s pc-scales after impact with GMC on the galaxy.
PHYSICAL STRUCTURES OF NGC 1068: TORUS

NGC 1068

Nuclear reflection cone (HST/FOC)

Optical galaxy (HST)

Obscuring torus? (VLBA)

Radio jet (MERLIN)

1"

0.01"
- CO is mainly distributed in the starburst ring.
- HC3N is abundant in the CND
- CS is distributed both in CNS and starburst ring.

PHYSICAL STRUCTURES OF NGC 1068: CO STARBURST RING

HC3N (yellow), CS (red), CO (blue) observed by ALMA
NGC 1068

V (0.606 μm - HST/WFPC2)
I (0.814 μm - HST/ACS)
Hα (0.658 μm - HST/ACS)
B-field (89 μm - SOFIA/HAWC+)
SPIRAL MAGNETIC FIELD: AXISYMMETRIC SPIRAL STRUCTURE MODEL I

Logarithmic spiral B-field ($\Psi$: pitch angle):

\[
\begin{align*}
B_x &= -B_0(r) \sin(\phi + \Psi) \cos \chi(z) \\
B_y &= B_0(r) \cos(\phi + \Psi) \cos \chi(z) \\
B_z &= B_0(r) \sin \chi(z)
\end{align*}
\]

B-field viewed at inclination, $i$, and tilt, $\theta$, angles:

\[
\begin{align*}
B_x^* &= B_x \cos \theta + (B_y \cos i - B_z \sin i) \sin \theta \\
B_y^* &= -B_x \sin \theta + (B_y \cos i - B_z \sin i) \cos \theta \\
B_z^* &= B_y \sin i + B_z \cos i
\end{align*}
\]
SPIRAL MAGNETIC FIELD: AXISYMMETRIC SPIRAL STRUCTURE MODEL I

Logarithmic spiral B-field (Ψ: pitch angle):

\[ B_x = -B_0(r) \sin(\phi + \Psi) \cos \chi(z) \]
\[ B_y = B_0(r) \cos(\phi + \Psi) \cos \chi(z) \]
\[ B_z = B_0(r) \sin \chi(z) \]

Bayesian inferred angles:

B-field viewed at inclination, \( i \), and tilt, \( \theta \), angles:

\[ B_{x*} = B_x \cos \theta + (B_y \cos i - B_z \sin i) \sin \theta \]
\[ B_{y*} = -B_x \sin \theta + (B_y \cos i - B_z \sin i) \cos \theta \]
\[ B_{z*} = B_y \sin i + B_z \cos i \]

Best family of solutions:

- P and PA varies as a function of the azimuthal angle, which arises from the projection and inclination of the disk field component in the plane of the sky
89 um: The logarithmic spiral model traces the star-forming regions along the spiral arms.
- Spiral between the optical at 0.46 um and the CO (J=1-0) emission (table).
- Spiral spatially coincident with the H$_\alpha$ velocity field and HII regions
  - HII regions were enhanced by a burst in the past 30 Myr (Davies, Sugai & Ward 1998)

### SPIRAL MAGNETIC FIELD: MULTI-WAVELENGTH COMPARISON

<table>
<thead>
<tr>
<th>Tracer</th>
<th>Pitch angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46 um</td>
<td>$20.6 \pm 4.5°$</td>
</tr>
<tr>
<td>R-band</td>
<td>$17.3 \pm 2.2°$</td>
</tr>
<tr>
<td>H$\alpha$ velocity field</td>
<td>$15°$</td>
</tr>
<tr>
<td>CO (J=1-0)</td>
<td>7-10°</td>
</tr>
<tr>
<td>89 um (HAWC+)</td>
<td>$16.9 \pm 2.8°$</td>
</tr>
</tbody>
</table>
- Within the central region (<2 kpc):
  - Large-scale coherent magnetic field aligned with the inner-bar (black line)
  - Spiral model cannot explain this area because the model does not fulfill the divergence-free requirement and/or the different magnetic field morphology.
Within the central region (<2 kpc):
- Zero-polarization occurs between the regions of most active star formation and the points at which the other spiral arms diverge from the starburst ring.
- The B-field directions from the model are in the sense of a larger radial component in the observed vectors.
- If B-field traces the gas flow, these results would be consistent with inward transport of gas at the leading edge of the inner-bar, with the highest present-day flow rates occurring along the NE branch of the bar.
Within the central region (<2 kpc):
  - Low-polarized AGN (black cross):
    - P ~0.6 ± 0.3% (89 um), 1.3±0.3% (53 um).

Radio-Loud AGN are highly polarized
Radio-quiet AGN are low polarized
**SUMMARY: THE MAGNETIC FIELDS OF NGC 1068**

- FIR polarimetric observations allow to trace the magnetic field in the dense ISM.
  - Optical-NIR suffers of electron/dust scattering
  - Radio polarimetry traces synchrotron polarization from relativistic electrons in the diffuse ISM

- A ~3 kpc large-scale spiral magnetic fields is measured on the disk of the galaxy.
  - A logarithmic spiral model with a pitch angle tracing the star-forming regions along the spiral arms can explain the large-scale spiral structure.

- Within the central region (<2 kpc):
  - Large-scale coherent magnetic field aligned with the inner-bar
  - Zero-polarization at the location of star-forming regions at the edges of the inner-bar.
  - Low-polarized AGN.