outline

• HAWC+ intro. & update
• GTO programs
• OMC1: magnetic field modeling
• grain alignment
• Galactic Center CNR
• other galaxies
HAWC+ facility far-IR camera/polarimeter for SOFIA

imaging and differential polarimetry with 3 @ 32x40 bolometer detector arrays

four wavelength bands: 53, 89, 154, 214 μm
HAWC+ filter bands cover the spectral peak of dust emission.

HAWC+ measures the polarization from dust aligned with respect to the magnetic field.
HAWC+ updates

- (Jan. 2017: last HAWC+ tele-talk)
- June – August 2017: further work on instrument internals, improving ADR run time and restoring 4 columns & 2 rows in detector readout
- October – November 2017: 15 full-length flights, ADR lasting through all; lots of data
- April 2018: HAWC+ instrument team completes work on instrument and pipeline; USRA/NASA takes over all responsibility
- July 2018: 8 very successful flights out of New Zealand

added a disc spring (Belleville washer) stack to each of 6 “hard” straps in summer 2017, for improved vibration isolation

figures from HAWC+ instrument paper (Harper, Runyan, Dowell, Wirth, et al., Journal of Astronomical Instrumentation, in press)
HAWC+ Guaranteed-Time Targets

• Magnetic field structure and strength in nearby molecular clouds: W3OH, Orion (OMC1), Vela C, Rho Oph A, M17, NGC 7023, isolated protostars

• Dust grain alignment: same targets observed in multiple wavelength bands

• Magnetic field structure of the Galactic center: Circum-Nuclear Ring, Sickle, wide field 89 μm survey

• Degree of polarization and magnetic field structure of resolved IR galaxies: NGC 253, NGC 891, NGC 1068, M82, M51

• Far-IR variability on year to decade timescales: SN1987A, NGC 6334I
Orion Molecular Cloud 1

(Chuss, Guerra, Michail, HAWC+ GTO, in prep.)
Orion Molecular Cloud 1

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Line Integral Convolution representation of magnetic field direction
Fine-Scale Structure in Magnetic Field

- Dispersion in magnetic field angles is related to strength of field (Davis ‘51; Chandrasekhar & Fermi ‘53):
  \[ \frac{B^2}{4\pi\rho\sigma^2(v)} \approx \frac{1}{(\Delta\phi)^2} \]
  Need to consider line-of-sight and beam averaging.

- Structure functions are a natural way to separate dispersion from turbulence from slowly-varying ordered field, and to learn about spectrum of turbulence (Hildebrand+ ‘09; Houde+ ‘16)

  (Chuss, Guerra, Michail, HAWC+ GTO, in prep.)

* input parameters: \( \rho, \sigma(v) \), depth of cloud
* fit parameters: turbulence correlation length, \( B_{\text{turb}}/B_0 \), 1 amplitude term for structure in ordered field
* output: \( B_0 \), # turbulent cells in beam
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dust grain alignment efficiency

- Our analysis for OMC-1 depends on dust polarization being a reliable tracer of the magnetic field direction.
- In *dark clouds*, at least, the alignment appears to become poor at high extinction.
  - diagnostic: trend in polarization efficiency with column density

![Graph showing the relationship between $p/A_V$ and $A_V$](chart.png)

- Uniform cloud would produce horizontal line (constant polarizing efficiency of grains).
- Decreasing polarizing efficiency (magnetic field structure? partial loss of grain alignment?)
- Slope of -1: complete loss of grain alignment (?)

*Observations are difficult and few in number.*

Andersson, Lazarian, & Vaillancourt (2015)
OMC-1: polarization vs. total intensity

- A mess!
- The trend in both the upper envelope and median is pretty flat.
effects of magnetic field structure on $p$

- Best predictor of $p$ for a line of sight is the dispersion of pol. angles in its vicinity.
- Expectation is $p \sim S^{-1}$, for a simple model of magnetic field structure (Planck Collab. '18)
- Following Fissel+ '16, fit trends with both $S$ and $I$: $p = p_0 \left( \frac{S}{\langle S \rangle} \right)^\alpha \left( \frac{I}{\langle I \rangle} \right)^\beta$
• Now that effect of magnetic field structure has been removed, we see nearly uniform grain alignment to $A_V > 200$. Presumably the many stars embedded in OMC-1 are important for this.
• Degree of polarization and polarization angles are both diagnostic of the magnetic field structure.
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$p$ might be suppressed by $\tau_{89 \mu m} \sim 1$.
What will HAWC+ see in cold, dark clouds?

- Very little GTO time is invested in $T < 20$ K dark clouds.
- Insights to grain alignment in such objects more likely to come from GO programs.
- The hint from analysis of Rho Oph A (Santos, HAWC+ GTO, in prep.) is that colder grains produce less far-IR polarization:
chop reference beams / need for method of large-area mapping

- HAWC+ measures polarization and intensity by chopping (differencing) vs. two reference positions <= 8 arcminutes away.
- Polarization at reference positions is unknown.
  - Systematic uncertainty estimated using Novak+ ‘97, Schleuning ‘98, Dotson+ ‘00
- We need a method of mapping large areas with HAWC+ beyond 8 arcminutes.
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Galactic center “Mini-Spiral” and Circum-Nuclear Ring (Lau+ '13)

- Circumnuclear disk structure is well-resolved => detailed study of accretion in a galactic nucleus
- Magnetic field measurements essential for assessment of forces on baryonic matter, may also show gas streamlines.
  - Existing measurements suggest mGauss strength.
near side of ring (Genzel ‘89)
approaching (Lester+ ‘81)
rotation direction from FIR/mm spectroscopy and NIR extinction
receding (Lester+ ‘81)
37 μm contours on 1.9 μm HST/NICMOS image
21
100 µm B vectors from KAO (Hildebrand+ ’93)

color scale:
53 µm Stokes I from SOFIA/HAWC+
100 µm B vectors from KAO (Hildebrand+ '93)

12.5 µm B vectors (Roche+ '18; see also Aitken+ '98)

color scale:
53 µm Stokes I from SOFIA/HAWC+
53 µm B vectors (HAWC+)

color scale:
53 µm Stokes I from SOFIA/HAWC+
Spiral magnetic field pattern consistent with known direction of rotation.

Field follows curve of most prominent elongated features.
• Spiral pattern evident in 53 μm magnetic field data to at least 60 arcsec (2.5 pc) radius.
simple model for region: logarithmic spiral field

- Initial purpose: characteristic pitch angle of spiral for inner 5 pc
- Model: wedge-shaped disk with $e^{r/r_0}$ distribution of dust emission, inclined 67°; magnetic field twisted 28° from radial direction.
In broad terms, model gives approximately the right average pitch angle.

Does not match detailed structure, however.
• intense and strongly-polarized emission from Northern Arm and vicinity of IRS 8
  • polarized emission extending beyond ring, perhaps associated with radio “wings” (Zhao+ ‘16)
  • contrast between moderate polarization at N&S ends and low polarization at E&W sides.
  > Can this be explained by field inclination ($p \approx p_0 \cos^2 i$)?
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logarithmic spiral model vs. observation

- Although some general trends may be captured by model, detailed structure is not.
disk with 3D self-similar magnetic field

field model “gc2” from Wardle & Königl ‘90 set, preferred (and modified) by Hildebrand+ ‘93
disk with 3D self-similar magnetic field

- This model also does not reproduce the detail in the data.
- Ordered disk models have 180° symmetry, unlike the data.
• Five 53 μm intensity and polarization features correspond to radio continuum features, with field parallel to all.

• Three molecular kinematic components correspond to 53 μm intensity features.
  – Two have field roughly following them.
  – One has very low polarization.

• Other suggested intensity/magnetic components in blue.
image credit:
HAWC+ GTO team
FORCAST (Lau+ ‘13)
HST/NICMOS
SOFIA/USRA
• Within central 2.5 pc radius, magnetic field shows a general spiral pattern with direction more radial than azimuthal.
  ➢ Orientation of spiral is consistent with known ring rotation direction.
• Some aspects of the observations are represented by models, but observations do not show 180° rotational symmetry of ordered disk models.
• In general, field appears to follow elongated structures in this region.

image credit:
HAWC+ GTO team
FORCAST (Lau+ ’13)
HST/NICMOS
SOFIA/USRA
E. Lopez-Rodriguez, HAWC+ GTO, in prep.
**galaxies: measured far-IR polarization**

<table>
<thead>
<tr>
<th>galaxy</th>
<th>structure</th>
<th>degree of pol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M82</td>
<td>nuclear starburst (Ø 0.8 kpc)</td>
<td>2.0 %</td>
</tr>
<tr>
<td>NGC 1068</td>
<td>nucleus + bar (Ø 0.8 kpc)</td>
<td>0.8 %</td>
</tr>
<tr>
<td>&quot;</td>
<td>starburst ring (Ø 2 kpc)</td>
<td>1.4 %</td>
</tr>
<tr>
<td>NGC 253</td>
<td>nucleus (Ø 0.6 kpc)</td>
<td>0.5 %</td>
</tr>
<tr>
<td>M51</td>
<td>face-on disk (inner Ø 8 kpc)</td>
<td>~2 % (prelim.)</td>
</tr>
<tr>
<td>NGC 891</td>
<td>edge-on disk (inner Ø 8 kpc)</td>
<td>t.b.d.</td>
</tr>
</tbody>
</table>

- Polarization is 0.5 – 2% on ~0.5 kpc scales
- This is measurable with systematic errors (<= 0.2%) already achieved in several instruments.
- Sensitivity from space (e.g. SPICA, Origins Space Telescope) would permit detailed magnetic field maps of nearby galaxies.
Summary

• HAWC+ is a facility instrument for SOFIA, providing far-infrared continuum imaging and polarization mapping.

• GTO and GO programs to map the magnetic field structure in Galactic clouds, the Galactic Center, and nearby infrared galaxies are underway.

• https://www.sofia.usra.edu/science/instruments/hawc