SOFIA@AAS 2019
HAWC+ Data Workshop

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Agenda

FORCAST:
● 08:30 — Introduction to FORCAST
● 09:00 — Introduction to FORCAST data pipeline and products
● 09:15 — DCS Archive demo for FORCAST
● 09:30 — FORCAST Grism Data Recipe: Inspection and Assessment
● 10:00 — Open time for exploration/break
● 10:30 — FORCAST Grism Data Recipe: Basic Line Analysis
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● 12:00 — Lunch break

HAWC+:
● 13:00 — Introduction to HAWC+ and polarimetry
● 13:30 — DCS Archive demo for HAWC+
● 13:45 — HAWC+ Data Recipe
● 15:15 — Break
● 15:45 — Open time for exploration
● 16:45 — Wrap up
● 17:00 — End

SOFIA Help Desk: sofia_help@sofia.usra.edu
SOFIA and Far-Infrared Astronomy
Observing on SOFIA
Imaging and Polarimetry with HAWC+
HAWC+ Filters

![Graph showing transmission of different bands across wavelengths](image)

- Band A
- Band B
- Band C
- Band D
- Band E

Transmission (%) vs. Wavelength (μm)
Inside HAWC+
HAWC+ TES detectors

Two arrays of co-aligned TES bolometers

- 32 x 40 pixel subarrays
- Total intensity:
  - R0 + R1
- Polarimetry
  - R0 + T0
- 0.3 K transition
- >12 hour hold time
### Instrument Parameters

<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” 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” 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” 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” 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” FWHM</td>
<td>8.0 x 6.1</td>
<td>4.0 x 6.1</td>
</tr>
</tbody>
</table>
HAWC+ PSF

SOFIA is diffraction-limited at all wavelengths

FWHM

4.7"

7.8"

14"

19"
Observing Modes

- Symmetrical Chop/Nod for polarimetry
- Total intensity scan mapping has two modes:
  - Lissajous: for small fields comparable to the FOV
  - Raster: for large mapping areas
- Part of the map should include regions with no extended emission
Lissajous Scanning

FOV

Telescope path
Polarization Basics

- Polarized light:
  - Stokes $I$ is the total intensity of the incoming light;
  - $P$ is the fraction of the light that is polarized;
  - $\theta$ is the angle of the polarization relative to celestial North.

- Linear Stokes parameters:
  - $Q = I P \cos(2\theta)$
  - $U = I P \sin(2\theta)$
Optical Path

- Detector arrays
- Filter/lens wheels
- HAWC Vacuum Window
- HAWC field mirror
- Folding mirror
- From SOFIA telescope
- Polarizer
- Cold pupil and rotatable half-wave plate
Half-wave Plate
Measuring Q & U with HAWC+

- Stokes $Q$: 
  $$Q = \frac{1}{2}[(R - T)_0 - (R - T)_{45}]$$

- Stokes $U$: 
  $$U = \frac{1}{2}[(R - T)_{22.5} - (R - T)_{67.5}]$$
Polarization Basics

- Polarization fraction $P$:
  \[ P = 100 \sqrt{\left(\frac{Q}{I}\right)^2 + \left(\frac{U}{I}\right)^2} \]

- Uncertainty $\sigma_P$:
  \[ \sigma_P = \frac{1}{I} \sqrt{\sigma_{Q,U}^2 + \sigma_I^2 P^2} \]

- Polarization angle $\theta$:
  \[ \theta = \frac{90}{\pi} \tan^{-1} \left(\frac{U}{Q}\right) \]

- Uncertainty $\sigma_\theta$:
  \[ \sigma_\theta = \frac{180^\circ}{\pi} \frac{\sigma_P}{2P} \]
De-biasing polarization

Vidal, Leahy & Dickinson 2015

Real signal-to-noise ratio

\[ P_0 \sim \sqrt{P^2 - \sigma_P^2} \]
Instrumental Polarization

Error on IP: $\sim 0.3 \%$
<table>
<thead>
<tr>
<th>Ext #</th>
<th>Ext Name</th>
<th>Type</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>STOKES I</td>
<td>img</td>
<td>Jy/pix</td>
<td>Stokes $I$ (total intensity)</td>
</tr>
<tr>
<td>1</td>
<td>ERROR I</td>
<td>img</td>
<td>Jy/pix</td>
<td>Error in $I$</td>
</tr>
<tr>
<td>2</td>
<td>STOKES Q</td>
<td>img</td>
<td>Jy/pix</td>
<td>Stokes $Q$</td>
</tr>
<tr>
<td>3</td>
<td>ERROR Q</td>
<td>img</td>
<td>Jy/pix</td>
<td>Error in $Q$</td>
</tr>
<tr>
<td>4</td>
<td>STOKES U</td>
<td>img</td>
<td>Jy/pix</td>
<td>Stokes $U$</td>
</tr>
<tr>
<td>5</td>
<td>ERROR U</td>
<td>img</td>
<td>Jy/pix</td>
<td>Error in $U$</td>
</tr>
<tr>
<td>6</td>
<td>IMAGE MASK</td>
<td>img</td>
<td>⋯</td>
<td>Weighted number of input pixels combined into output pixels</td>
</tr>
<tr>
<td>7</td>
<td>PERCENT POL</td>
<td>img</td>
<td>%</td>
<td>Polarization percent $p = 100\sqrt{(Q/I)^2 + (U/I)^2}$</td>
</tr>
<tr>
<td>8</td>
<td>DEBIASED PERCENT POL</td>
<td>img</td>
<td>%</td>
<td>Debiased polarization percent $p' = \sqrt{p^2 - \sigma_p^2}$</td>
</tr>
<tr>
<td>9</td>
<td>ERROR PERCENT POL</td>
<td>img</td>
<td>%</td>
<td>Error in $p'$</td>
</tr>
<tr>
<td>10</td>
<td>POL ANGLE</td>
<td>img</td>
<td>deg</td>
<td>Polarization angle ($\theta$) in sky coordinates</td>
</tr>
<tr>
<td>11</td>
<td>ROTATED POL ANGLE</td>
<td>img</td>
<td>deg</td>
<td>Polarization angle ($\theta_{90}$) rotated by 90°</td>
</tr>
<tr>
<td>12</td>
<td>ERROR POL ANGLE</td>
<td>img</td>
<td>deg</td>
<td>Error in $\theta$</td>
</tr>
<tr>
<td>13</td>
<td>POL FLUX</td>
<td>img</td>
<td>Jy/pix</td>
<td>Polarized intensity $I_p = I \times p/100$</td>
</tr>
<tr>
<td>14</td>
<td>ERROR POL FLUX</td>
<td>img</td>
<td>Jy/pix</td>
<td>Error in $I_p$</td>
</tr>
<tr>
<td>15</td>
<td>DEBIASED POL FLUX</td>
<td>img</td>
<td>Jy/pix</td>
<td>Debiased polarized intensity $I_{p'} = I \times p'/100$</td>
</tr>
<tr>
<td>16</td>
<td>MERGED DATA</td>
<td>tab</td>
<td>⋯</td>
<td>Detector info from all merged images in cube</td>
</tr>
<tr>
<td>17</td>
<td>POL DATA*</td>
<td>tab</td>
<td>⋯</td>
<td>Polarization data for each pixel</td>
</tr>
<tr>
<td>18</td>
<td>FINAL POL DATA†</td>
<td>tab</td>
<td>⋯</td>
<td>Subset of POL DATA with quality cuts</td>
</tr>
</tbody>
</table>
Polarimetry

1. Chop-nod:
   - Nod parallel to chop, symmetric only
   - Chop-throw <8 arcmin, Chop-freq. 5-20 Hz

2. Half-WavePlate (HWP) rotation:
   - 4 HWP positions: 0°, 45°, 22.5°, and 67.5°
   - Chop-nod at each HWP angle

3. Dithering:
   - 4 dither positions within the FOV
   - Repeat chop-nod and HWP rotation at each dither position

4. Mosaics:
   - Steps 1 to 3 are repeated for a new sky position
Symmetric Chop/Nod

Nod Match Chop:
Nod A:

Chop position 1  Boresight  position 2

Chop Throw

Chop Position 1  Boresight  Position 2

Nod B:

Chop Throw

Nod Throw
Polarimetry Dithering
Resulting Polarization Maps

30 Doradus
Conclusion
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