Studying the influence of magnetic fields in star formation with submillimeter polarimetry

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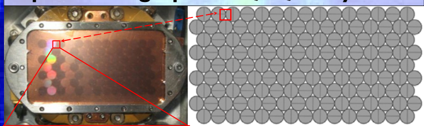
Abstract

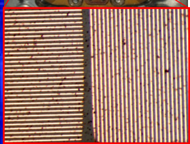
Submillimeter polarimetry provides an effective means of studying the role of magnetic fields in the earliest, highly obscured stages of star formation, via the polarized emission from aligned elongated dust grains. The Cardiff Astronomy Instrumentation Group has pioneered the development of submillimeter and millimeter-wave polarimeters by designing, manufacturing, and testing crystal and metal-mesh achromatic half-wave plates (HWPs), as well as their dielectric and meta-material anti-reflection coatings. These cutting-edge technologies have been successfully implemented in several ongoing experiments (e.g., BLAST-Pol, SCUBA-2, PILOT). Here we review the BLAST-Pol polarimeter and its ability to recover Stokes Q (or U) from a single scan, while different HWP positions allow measurement of the other one through polarization rotation. We also present a new method to account for the HWP non-idealities in the map-making algorithm, which we have implemented to obtain polarization measurements of unprecedented accuracy at 250, 350, and 500 μm.

Submillimeter polarimetry

- measure direction and strength of the plane-of-the-sky component of the magnetic field by tracing the linearly polarized thermal emission from aligned dust grains
- probe the role of magnetic fields in dust-enshrouded star-forming molecular clouds in our Galaxy
- the combination of maps obtained with experiments such as BLAST-Pol and SCUBA-2 will trace magnetic structures in the cold ISM from scales of 0.01 pc out to 5 pc, and help discriminate between models of star formation driven by magnetic fields or turbulent gas flows

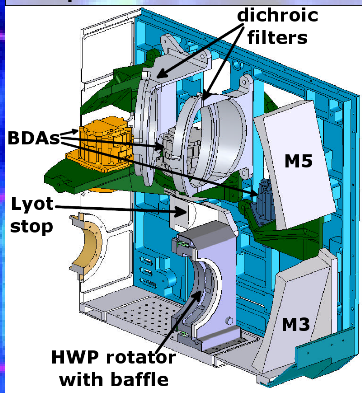
photolithographed +Q/-Q analyzers

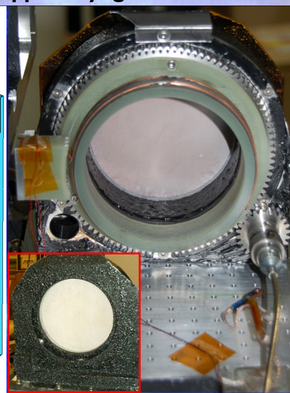




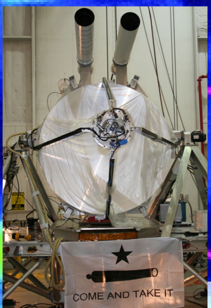
- photolithographed polarizing grids
- act as high-efficiency analyzers
- 5 μm copper strips – 5μm gaps
- alternate the polarization angle by 90° from bolometer-to-bolometer along the scan direction (+Q/-Q)

polarization modulation – stepped cryogenic HWP

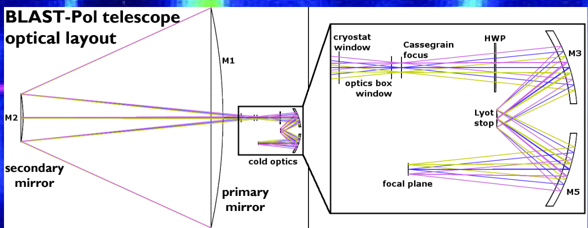




- achromatic 5-plate sapphire half-wave plate (HWP) built using the Pancharatnam (1955) design
- broadband polypropylene artificial dielectric anti-reflection coating (see Zhang et al. 2009)
- HWP is operated at 4K and is stepped by 22.5° every 15 minutes in flight
- sapphire absorption is minimized at 4K, though not completely suppressed (especially at 250 μm)



BLAST-Pol telescope optical layout



BLAST-Pol

for a description of the instrument, its science goals and targets, see posters of F. Elio Angile and Laura Fissel.

In a nutshell

- 2m Cassegrain telescope
- flown at 40km on a stratospheric balloon
- 270 bolometers at 250, 350, and 500 μm
- scan the sky at 0.1°/s with arcminute resolution and high sensitivity

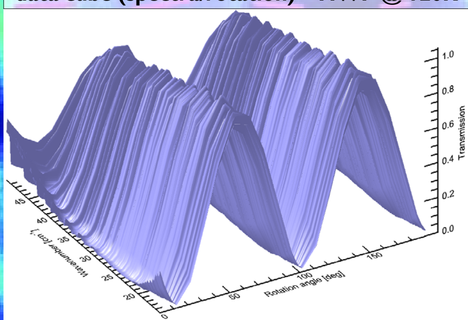
Optimal polarization recovery strategy

- differences of adjacent detectors give Q, but require accurate knowledge of their optical efficiencies η and suffer from 1/f noise
- the presence of a HWP compensates for the above effects, and provides polarization modulation to recover U without grids at 45/135°
- take differences of adjacent detectors, at two HWP positions that are 45° apart:

$$q_{\rm sky} = \frac{[d_1(\theta=0°) - d_2(\theta=0°)] - [d_1(\theta=45°) - d_2(\theta=45°)]}{[d_1(\theta=0°) + d_2(\theta=0°)] + [d_1(\theta=45°) + d_2(\theta=45°)]}$$

$$u_{\rm sky}\Big|_{\theta=[22.5°,\,67.5°]} = \frac{\eta_1(I_y - I_x) + \eta_2(I_y - I_x)}{\eta_1(I_y + I_x) + \eta_2(I_y + I_x)} = \frac{(I_y - I_x)}{(I_y + I_x)}\,.$$

data cube (spectra/rotation) – HWP @ 120K



- data cube acquired using a polarizing Fourier transform spectrometer
- HWP is rotated between parallel polarizers and spectra are taken
- slices of surface along the angle axis are the HWP modulation curves
- HWP has a different response between perpendicular polarizers
- both data cubes are necessary to fully spectrally characterize the HWP

the photometric equation for a real HWP

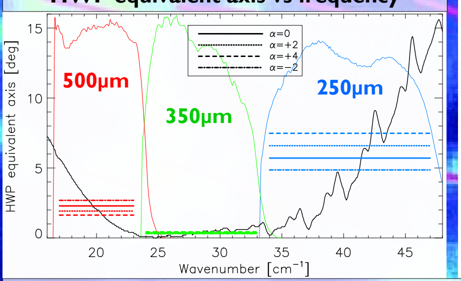
optical eff. $\eta = a_{00} + \frac{a_{11}}{2} + \frac{a_{22}}{2}$ polarization eff. $\eta\varepsilon = \frac{a_{11}}{2} - \frac{a_{22}}{2}$

$$d_t^i = \frac{\eta_t^i}{2} A_{tp}^i \left[I_p + \varepsilon^i \left(Q_p \cos 2\gamma_t^i + U_p \sin 2\gamma_t^i\right)\right] + n_t^i$$

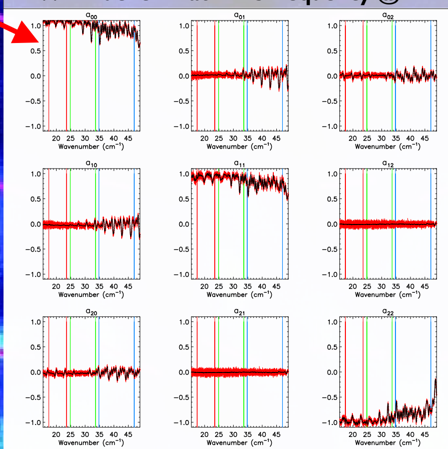
$$\gamma_t^i = \underbrace{\alpha_t^i}_{\text{pointing}} + 2\,[\underbrace{\beta_t}_{\text{HWP angle}} - \underbrace{\beta_0}_{\text{HWP zero angle}} - \bar{\beta}_{ea}] + \underbrace{\delta^i_{grid}}_{[0,\,\pi/2]}$$

$i \rightarrow$ detector, $t \rightarrow$ time, $p \rightarrow$ pixel

HWP equivalent axis vs frequency



HWP Mueller matrix vs frequency @ 4K



- an empirical model allows us to recover the HWP Mueller matrix as a function of frequency
- we extrapolate the HWP Mueller matrix measured at 120K to 4K using data from the literature
- the knowledge of the position of the HWP equivalent axis as a function of frequency allows us to diagonalize the HWP Mueller matrix, which then approaches that of an ideal HWP
- the band-integrated position of the HWP equivalent axis depends on the spectrum of the input source (particularly at 250 and 500 μm), while the band-integrated coefficients of the HWP Mueller matrix do not; however, they still factor in as optical and polarization efficiencies
- all these corrections can be concurrently included in a map-making algorithm

@ θ=0

$$\mathcal{M}_{\rm HWP}^{\rm ideal} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Conclusions

We have presented the polarization modulation scheme that has been successfully retrofitted on BLAST-Pol. We have performed a full spectral characterization at cryogenic temperatures, of the five-plate sapphire BLAST-Pol HWP, which is, to our knowledge, the most achromatic ever built at mm and submm wavelengths. We have found that most of the non-idealities of the HWP assembly can be accounted for by quantifying one frequency-dependent parameter, the position of the equivalent axes of the HWP, as a function of the spectral signature of a given astronomical source. We have subsequently included this parameter in the BLAST-Pol map-maker. BLAST-Pol has completed in January 2011its first successful 9.5-day flight over Antarctica, mapping ten star-forming regions with unprecedented combined mapping speed, sensitivity and resolution. These maps comprise an exciting dataset for studying the role played by magnetic fields in star formation. The polarization maps are currently being finalized, stay tuned at http://blastexperiment.info/.

References: Moncelsi et al., 2011, in preparation – Savini et al., 2006, Appl. Opt., 45, 8907 – Pisano et al., Appl. Opt., 47, 6251 – Savini et al., 2009, Appl. Opt., 48, 2006 – Zhang et al., 2009, Appl. Opt., 48, 6635