MAXIPOL

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- NA Balloon Borne
- Based on MAXIMA
- Pathfinder for HWP-based CMB Polarimetry
MAXIPOL Collaboration

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Hardware

- NTD-based spider-web bolometers (Bock)
- Cooled to 0.1 K
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Observations

- 7.6 hours centered on BUM; 4.1±0.8 μK dust brightness
- Constant elevation scans: 2 deg p-p, 15 sec period
- 5.3 square degrees used for analysis
- Day+night Jupiter calibration scans
Maps and EE Power

Graph showing the power spectrum of the Cosmic Microwave Background (CMB) with different polarization maps. The graph plots $l(l+1)C_l/2\pi$ (in $\mu K^2$) against the multipole moment $l$. The data points represent observations from various experiments including MAXIPOL, CAPMAP, DASI (05), CBI (05), B03, and WMAP. The plot includes a best-fit line for the matter-antimatter model ($\Lambda$CDM).

Observational Cosmology - University of Minnesota
Rotating HWP Polarimetry

Amplitude and phase = P magnitude and orientation

Time (signal modulated at $4f_0$)
Rotating HWP Polarimetry

Amplitude and phase = P magnitude and orientation

HWP Angle
(4 modulations per full rotation)

- I, Q, U from the same detector
- Q, U at high frequencies
- Q, U near 4x rotation frequency
- Same beam for orthogonal polarization states
Frequency of $T, Q, U$

- Time domain signal $S(t) = A \cos\left[2\pi (4f_0)t + \phi\right]$
- Scanning the telescope across the sky modulates $A$ (and $\Phi$)

$$S(t) = A(t) \cos\left[2\pi (4f_0)t + \phi\right] = A_0 \sin \omega t \cos\left[2\pi (4f_0)t + \phi\right] \propto \sin[(2\pi (4f_0) + \omega) t + \phi] + \sin[(2\pi (4f_0) - \omega) t + \phi]$$

- Scan synchronous $Q, U$ signal appears at sidebands of 4th harmonic
Polarimetry Hardware
Instrumental Polarization

- Conversion of un-polarized intensity to Q, U
- Modulated by HWP, if on sky side
- Sources
  - Differential reflection+transmission
  - Polarized emission
  - Polarization by diffraction

Sky sources - scan synchronous
Instrument sources - stable
**Instrumental Polarization**

- CMB $T \rightarrow Q, U$
- Primary (+secondary) $T \rightarrow Q, U$

- CMB $T \rightarrow Q, U$: 1% IP $= 27 \text{ mK}$
- CMB $\Delta T \rightarrow Q, U$: 1% IP $\sim 1 \mu\text{K}$
- Primary $T \rightarrow Q, U$: 1% IP $= 24 \text{ mK}$

- Reflection $T \rightarrow Q, U$
- Reflection $\Delta T \rightarrow Q, U$

- Emission (240 K, 1%)
- Polarized emission
Instrumental Polarization

- CMB T→Q,U
- Primary (+secondary) T→Q,U

- CMB T→Q,U: 1% IP = 27 mK
- CMB ∆T →Q,U: 1% IP ~1 μK
- Primary T→Q,U: 1% IP = 24 mK

P = 0 torr
P = 760 torr

window
• Knife edge diffraction
  – Can have P = 100%
  – P = 10% of 6K gives 600 mK

• Shaft T anisotropy
• Shaft emissivity anisotropy
• Shaft motion in beam
Time Domain Data
Rotation Synchronous Signal

- Raw data in HWP angle
- Power Spectrum
- Shaft Rotation
- Differential Reflection
- Instrumental Polarization
Fit for Synchronous Signal

\[ HWPSS(t) = \sum_{n=1}^{8} \sum_{j=1}^{3} (A_{nj} + B_{nj}t) \sin(n\beta(t) + \phi_{nj}) \]

Amplitudes

- \( n=1 \): 1.5-106 mK
- \( n=2 \): 30-250 mK
- \( n=4 \): 33-600 mK

Amplitude drift

- 0.5% over 10 minutes

Varying amplitude

Constant phase
Synchronous Signal Removed

Power spectrum of Q, U:
99.5% of data
1/f knee < 60 mHz

synchronous signal removed
• Remnants of SS in CMB signal? Removal of CMB signal?
  – No. \((\text{simulated } Q - \text{recovered } Q)/\text{simulated } Q < 0.5\%\)

• Gaussianity of Q, U?
Scan Synchronous Component?

T map

U map
Scan Synchronous Component?

- Scan Synchronous IP is less than 1% for 10/12 photometers
- 4%, 5% for 2/12 (at edge of field)
- A uniform 4% IP would give undetectable level in our data
Polarization Rotation

- $5 \text{ deg} \rightarrow 0.2 \, \mu \text{K reduction in EE}$

- Measurement with $P=1$ source at window

- Calibrates HWP offset + pol. Rotation
Rotation Error Budget

- Instrument coordinates to sky coordinates: 2 degrees
  - Rotation of star camera relative to mm-wave beam

- HWP offset + internal pol. rotation: 2 degrees
  - Alignment of outside grid to analyzer grid

- Primary pol. rotation < 1 deg

- Error from polarization rotation is < 5 degrees
Rotation and CodeV

Polarization Rotation x10 (deg)

- Subtract mean rotation
- Mean absolute difference = 1.2°
MAXIPOL Summary

[Astro-ph:0611394 (instrument + results); 0611396 (data analysis)]

• MAXIPOL demonstrated a successful implementation of HWP polarimetry in CMB

• Stable offsets removed with no detectable residuals

• Q, U temporal power spectra
  – white to ~1 mHz
  – level consistent with detector+readout noise

• Residual scan synchronous IP and Pol. Rotation negligible.

• Continuous rotation + NTD-based bolometers: a substantial challenge