Primordial Inflation Explorer (PIXIE)

Al Kogut
Goddard Space Flight Center
Primordial Inflation Explorer

Measure B-Mode Polarization
To Limits Imposed By Astrophysical and Cosmological Foregrounds
B-Mode Fundamentals

WMAP 23 GHz Polarization

Signal is faint
Foregrounds are bright
Everything is confusing

Requirements for B-Mode Detection
• Sensitivity
• Foreground Subtraction
• Systematic Error Control
Optical Design for CMB

Sky

Optics

Airy Disk

Conventional Focal Plane

Single-Moded Pixel
Optical Design for CMB

Conventional Focal Plane

Photon Limit: Add Detectors
Optical Design for CMB

Problem: Getting enough sensitivity in enough frequency bands requires 10,000 background-limited detectors!
PIXIE Optical Solution

PIXIE

Need more photons, not more detectors!

Replace tiled focal plane with multi-moded concentrator
PIXIE Optical Solution

Sky

Optics

FTS Phase Shift

Aperture

Concentrator

Detector

PIXIE

Replace multi-color detectors with Fourier transform spectrometer

Replace tiled focal plane with multi-moded concentrator

Win-Win: Sensitivity and spectra from a single detector
PIXIE Nulling Polarimeter

Measured Fringe Pattern
Samples Frequency Spectrum of Polarized Sky Emission

\[ P_{Lx} = \frac{1}{2} \int \left( E_{Ay}^2 + E_{Bx}^2 \right) + \left( E_{Bx}^2 - E_{Ay}^2 \right) \cos\left(\frac{z \omega}{c}\right) \, d\omega \]

\[ P_{Ly} = \frac{1}{2} \int \left( E_{Ax}^2 + E_{By}^2 \right) + \left( E_{By}^2 - E_{Ax}^2 \right) \cos\left(\frac{z \omega}{c}\right) \, d\omega \]

Stokes Q

Nulling Polarimeter: Zero = Zero

Kogut et al. 2011, JCAP, 7, 025
Kogut et al. 2011, SPIE, 7731, 77311S
PIXIE Non-Imaging Optics

Parameter | Value
--- | ---
Primary Mirror Diam | 550 mm
Etendu | $4 \text{ cm}^2 \text{ sr}$
Beam Diam | $2.6^\circ$ Tophat
Throughput | 82%

44,000 modes on 4 detectors
Instrument Cryogenics

- Fully cryogenic instrument
  - Cryo-cooler to 4.5 K
  - ADR to 2.7 K (instrument body)
  - ADR to 0.1 K (detectors)

- Tolerant thermal design
  - Robust design/performance margins
  - Active thermal control for all optical surfaces
  - Thermal “backbone” tolerant vs temperature excursions
Instrument and Observatory

- Spin 4 RPM
- Polarizing Fourier Transform Spectrometer
- Instrument (2.725 K)
- Primary Mirror A
- Detectors (100 mK)
- Thermal Isolation
- Sun/Earth Shields
- Solar Arrays
- Spacecraft
- To Sun
- To Earth
Observatory

Stowed in Taurus-I ELV

Spacecraft Bus
Solar Arrays

Thermal Shields

PIXIE Coordinate System
IAU (STPSat 2)
ICDU (Instrument)
Reaction Wheel (Heritage Classified)
Torque Rod (Aft Side of Bus, WISE Heritage)
Star Scanner (ACE Heritage)
Battery (Kepler Heritage)

S-Band Antenna (WISE Heritage)
S-Band Transponder (Top Deck of Bus, LRO Heritage)
Magnetometer (WISE Heritage)
CCE (Instrument)
Structure (WISE Heritage)
MIMU (GPS II Heritage)

Star Power (for scale)

Top View
1.98m
1.70m

2.75m
1.69m
.58m

Separation Plane
.97m

Payload Launch Adapter
PIXIE Mission Concept

Polar Sun-Synch Orbit
- 6 AM or 6 PM ascending node
- 660 km altitude

3-Axis Control
- Spin at 4 RPM
- Spin axis 90° to sun line
- Zenith view (precess axis once/orbit)

Routine Observations
- Spin and stare
- Move calibrator every 2nd orbit
- 2 year baseline mission
- 4 year extended mission

Small observatory fits multiple launch vehicles
- Taurus-I ELV

Like COBE, but lower
COBE, WMAP
COBE, WMAP, Planck

Full-Sky Maps in Stokes IQU in 400 Channels 30 GHz to 6 THz
So What’s The Problem?

Signal is faint
Foregrounds are bright
Everything is confusing

Requirements for B-Mode Detection
- Sensitivity
- Foreground Subtraction
- Systematic Error Control
Sensitivity Matched to CMB Lensing

Full-sky maps in Stokes I, Q, U
NET = 13.6 µK s$^{1/2}$ (Stokes I)
NEQ = 5.6 µK s$^{1/2}$ (Stokes Q, U)

Beam independent of frequency
Tophat diameter 2.6° (FWHM ~ 1.6°)
Multipoles $2 < \ell < 200$

Sensitivity 70 nK per 1° x 1° pixel

B-mode limit $r < 0.001$ (5σ)
Foreground Subtraction

**Sensitivity plus broad frequency coverage**
- Foreground S/N $> 100$ in each pixel and freq bin
- Spectral index uncertainty $\pm 0.001$ in each pixel
- Dust physics to inform foreground subtraction

**Spectral coverage spanning 7+ octaves**
- Polarized spectra from 30 GHz to 6 THz
- 400 channels to fit 15 free parameters
- Foreground noise penalty only 2%
Polarization depends on composition
  • Silicate: Colder, More polarized
  • Carbonaceous: Warmer, Less polarized

Sensitive probe of dust composition

PIXIE data from 30 GHz to 6 THz
  • Temperature(s)
  • Fractional polarization
  • Chemical composition

Constrain dust properties for each line of sight

Hildebrand & Kirby 2004
Systematic Error Control
Multiple Instrumental Symmetries

Spacecraft spin imposes amplitude modulation of entire fringe pattern

Same information 4x per stroke with different time/space symmetries

Multiple Redundant Symmetries Allow Clean Instrument Signature
## Systematic Error Budget

**Efficient suppression of potential systematic errors**

<table>
<thead>
<tr>
<th>Symmetry</th>
<th>Mitigates</th>
</tr>
</thead>
<tbody>
<tr>
<td>x vs y Polarization</td>
<td>Beam/pointing</td>
</tr>
<tr>
<td>Left vs Right Detector</td>
<td>Beam/pointing</td>
</tr>
<tr>
<td>A vs B Beam</td>
<td>Differential loss</td>
</tr>
<tr>
<td>Real vs Imaginary FFT</td>
<td>1/f noise, relative gain</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
P_{Lx} &= \frac{1}{2} \int \left( E_{Ay}^2 + E_{Bx}^2 \right) + \left( E_{Bx}^2 - E_{Ay}^2 \right) \cos(z\omega/c) \, d\omega \\
P_{Ly} &= \frac{1}{2} \int \left( E_{Ax}^2 + E_{By}^2 \right) + \left( E_{By}^2 - E_{Ax}^2 \right) \cos(z\omega/c) \, d\omega \\
P_{Rx} &= \frac{1}{2} \int \left( E_{Ax}^2 + E_{By}^2 \right) + \left( E_{Ax}^2 - E_{By}^2 \right) \cos(z\omega/c) \, d\omega \\
P_{Ry} &= \frac{1}{2} \int \left( E_{Ay}^2 + E_{Bx}^2 \right) + \left( E_{Ay}^2 - E_{Bx}^2 \right) \cos(z\omega/c) \, d\omega
\end{align*}
\]

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### Table: Systematic Effects

<table>
<thead>
<tr>
<th>Effect</th>
<th>Leakage</th>
<th>PIXIE Mitigation</th>
<th>Residual (nK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-polar beam</td>
<td>E→B</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Beam ellipticity</td>
<td>▽²T→TB</td>
<td>✓ ✓</td>
<td>2.7</td>
</tr>
<tr>
<td>Polarized sidelobes</td>
<td>ΔT→B</td>
<td>✓ ✓</td>
<td>1.1</td>
</tr>
<tr>
<td>Instrumental polarization</td>
<td>ΔT→B</td>
<td>✓ ✓ ✓</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Polarization angle</td>
<td>E→B</td>
<td>✓ ✓</td>
<td>0.7</td>
</tr>
<tr>
<td>Beam offset</td>
<td>ΔT→B</td>
<td>✓ ✓ ✓</td>
<td>0.7</td>
</tr>
<tr>
<td>Relative gain</td>
<td>ΔT→B</td>
<td>✓ ✓ ✓</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Gain drift</td>
<td>T→B</td>
<td>✓ ✓</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Spin-synchronous emission</td>
<td>ΔT→B</td>
<td>✓ ✓ ✓</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Spin-synchronous drift</td>
<td>T→B</td>
<td>✓ ✓</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

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**Diagram:** The diagram illustrates the interaction of beams (A and B) and detectors (L and R) in the context of analyzing systematic errors. The layout helps visualize the beam paths and detector interactions.
Unique Science Capability

- Inflation/GUT Physics
- Reionization/First Stars
- CIB/Star Formation History
- ISM and Dust Cirrus

Multiple Science Goals

B-mode limit: \( r < 0.001 \) at 5\( \sigma \)

Full-Sky Spectro-Polarimetric Survey

- 400 frequency channels, 30 GHz to 6 THz
- Stokes I, Q, U parameters
- 49152 sky pixels each 0.9° × 0.9°
- Pixel sensitivity \( 6 \times 10^{-26} \) W m\(^{-2}\) sr\(^{-1}\) Hz\(^{-1}\)
- CMB sensitivity 70 nk RMS per pixel

Wavelength

Frequency (GHz)

Intensity (W / m\(^2\) / sr / Hz)

Angular Scale (Deg)

Multipole \( \ell \)
Design Trades (No Free Lunch)

**Penalties**
- Concentrator vs Focal Plane Array
- Angular Resolution (x6 at 2 mm)
- FTS vs Bandpass Filters
- Noise (x2)

**Advantages**
- Fewer Detectors (x1000)
- More Frequency Channels (x25)
- Broader Frequency Range (x8)
- Smaller Cold Area (x500)

Plus: Absolute spectra provide “insurance” against possible B-mode null result
PIXIE Technology

Technologically Mature Implementation

Polarization-Sensitive Detector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Requirement</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>160 mm$^2$</td>
<td>&lt;10$^{-16}$</td>
<td>0.7 x 10$^{-16}$</td>
</tr>
<tr>
<td>Fill Fraction</td>
<td>11%</td>
<td>&lt;4</td>
<td>1</td>
</tr>
<tr>
<td>Frame Temperature</td>
<td>100 mK</td>
<td>&lt;1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Absorber Temperature</td>
<td>140 mK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEP (W Hz$^{1/2}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time Constant (ms)</td>
<td>&lt;4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-Pol at 150 GHz</td>
<td>&lt;1%</td>
<td></td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Mirror Transport Mechanism
PIXIE Status

Proposed to 2011 Explorer AO
• $200M Cost Cap + launch vehicle
• 22 full missions

PIXIE not selected; urged to re-propose
• Category I science rating
• Broad recognition of science appeal
• Absolute spectra “guaranteed science”

Re-propose to next full Explorer AO
• 2015 proposal for 2021 launch?
Backup Slides
Sensitivity: Background Limit the Easy Way

Big Detectors in Multi-Moded Light Bucket

\[
\text{NEP}^2_{\text{photon}} = \frac{2A\Omega (kT)^5}{c^2 \hbar^3} \int \frac{\alpha \epsilon f}{e^x - 1} \left( 1 + \frac{\alpha \epsilon f}{e^x - 1} \right) \, dx
\]

\[
\delta I_{\nu} = \frac{\delta P}{A\Omega \Delta \nu (\alpha \epsilon f)}
\]

30x collecting area as Planck bolometers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Calibrator Deployed</th>
<th>Calibrator Stowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stokes I (per bin)</td>
<td>W m(^{-2}) sr(^{-1}) Hz(^{-1})</td>
<td>2.4 x 10(^{-22})</td>
<td>---</td>
</tr>
<tr>
<td>Stokes Q (per bin)</td>
<td>W m(^{-2}) sr(^{-1}) Hz(^{-1})</td>
<td>3.4 x 10(^{-22})</td>
<td>0.5 x 10(^{-22})</td>
</tr>
<tr>
<td>NET (CMB)</td>
<td>µK s(^{-1/2})</td>
<td>13.6</td>
<td>---</td>
</tr>
<tr>
<td>NEQ (CMB)</td>
<td>µK s(^{-1/2})</td>
<td>19.2</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Photon noise \(\sim (A\Omega)^{1/2}\)
Big detector: Negligible phonon noise

Signal \(\sim (A\Omega)\)
Big detector: S/N improves as \((A\Omega)^{1/2}\)

Sensitivity 70 nK per 1° x 1° pixel

PIXIE: \(A\Omega = 4 \text{ cm}^2 \text{ sr}\)
Foregrounds : Multiple Channels the Easy Way

Fourier Transform Spectrometer

- $S_\nu = \sum_{k=0}^{N_s-1} S_i \exp(2\pi i \nu k/N_s)$
- $S_i = \int S_\nu \exp(2\pi iz_i/c) d\nu$

Fringe Brightness vs Mirror Position $z$

Frequency Spectrum vs Fringe Pattern
Largest optical phase delay (1 cm) sets channel width
Number of samples (1024) sets number of channels

PIXIE: 512 channels each 15 GHz wide
Lowest effective channel = 30 GHz (1 cm)
Highest effective channel ~ 6 THz (50 µm)

Pixel-by-pixel foreground subtraction
400 effective channels to fit ~15 free parameters
Spectral index uncertainty ±0.001 in each pixel
Continuum spectra: curvature, multiple components, ...

Only 2% "noise penalty" for foreground subtraction
PIXIE Fourier Transform

Phase delay $L$ sets channel width
\[ \Delta \nu = \frac{c}{L} \]

Number of samples sets frequency range
\[ N_{\text{chan}} = \frac{N_{\text{samp}}}{2} \]

PIXIE: \(~400\) usable channels
\[ \Delta \nu = 15 \text{ GHz} \]
\[ 30 \text{ GHz} \text{ to } 6 \text{ THz} \ (1 \text{ cm to } 50 \mu \text{m}) \]

\[ S_{\nu} = \sum_{k=0}^{N_s-1} S_i \exp\left(2\pi i \nu k/N_s\right) \]

\[ S_i = \int S_{\nu} \exp\left(2\pi i z_i/c\right) d\nu \]

<table>
<thead>
<tr>
<th>Optical Delay</th>
<th>Physical Stroke</th>
<th>Samples per Stroke</th>
<th>Strokes per Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pm 10 \text{ mm}$</td>
<td>$\pm 2.5 \text{ mm}$</td>
<td>1024</td>
<td>8</td>
</tr>
<tr>
<td>$\pm 8.9 \text{ mm}$</td>
<td>$\pm 2.3 \text{ mm}$</td>
<td>910</td>
<td>9</td>
</tr>
<tr>
<td>$\pm 8.0 \text{ mm}$</td>
<td>$\pm 2.1 \text{ mm}$</td>
<td>819</td>
<td>10</td>
</tr>
<tr>
<td>$\pm 6.7 \text{ mm}$</td>
<td>$\pm 1.7 \text{ mm}$</td>
<td>683</td>
<td>12</td>
</tr>
<tr>
<td>$\pm 5.0 \text{ mm}$</td>
<td>$\pm 1.3 \text{ mm}$</td>
<td>512</td>
<td>16</td>
</tr>
<tr>
<td>$\pm 3.3 \text{ mm}$</td>
<td>$\pm 0.9 \text{ mm}$</td>
<td>341</td>
<td>24</td>
</tr>
</tbody>
</table>

Vary stroke length to apodize Fourier transform.
Layered Hybrid For Maximum Efficiency
• Thermal Shields: Cooling at 150K
• Cryocooler: Cooling at 68, 17, and 4.5K
• ADR: Cooling at 2.6 and 0.1 K

<table>
<thead>
<tr>
<th>Cooler Stage</th>
<th>Stage Temp (K)</th>
<th>CBE Loads (mW)</th>
<th>Derated Capability (mW)</th>
<th>Contingency &amp; Margin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stirling (Upper Stage)</td>
<td>68</td>
<td>2362</td>
<td>4613</td>
<td>95%</td>
</tr>
<tr>
<td>Stirling (Lower Stage)</td>
<td>17</td>
<td>132</td>
<td>278</td>
<td>111%</td>
</tr>
<tr>
<td>Joule-Thomson</td>
<td>4.5</td>
<td>20</td>
<td>40</td>
<td>100%</td>
</tr>
<tr>
<td>iADR</td>
<td>2.6</td>
<td>6</td>
<td>12</td>
<td>100%</td>
</tr>
<tr>
<td>dADR</td>
<td>0.1</td>
<td>0.0014</td>
<td>0.03</td>
<td>2043%</td>
</tr>
</tbody>
</table>

NOTE: Heat flow values in mW.
Cryogenics

Multi-Stage Cryogenic Design
- Passive Sun Shades (not shown)
- 4.5 K Cryo-cooler
- 2.7 K ADR
- 0.1 K ADR

Thermal Lift Budget

<table>
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<tr>
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Polarization-Sensitive Detectors

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<tr>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Mirror Transport Mechanism

Translate ±2.54 mm at 0.5 Hz
Optical phase delay ±1 cm
Repeatable cryogenic position

Engineering prototype

Demonstrated performance exceeds requirement by factor of ten
Blackbody Calibrator

Based on successful ARCADE calibrator

Note: Not To Scale

<table>
<thead>
<tr>
<th>XCal Requirements</th>
<th>Parameter</th>
<th>Requirement</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blackness (30 to 300 GHz)</td>
<td>&lt; -60 dB</td>
<td>-65 dB</td>
</tr>
<tr>
<td></td>
<td>Blackness (&gt; 300 GHz)</td>
<td>&lt; -20 dB</td>
<td>-50 dB</td>
</tr>
<tr>
<td></td>
<td>Temperature Range (Body)</td>
<td>2.6 - 3.5 K</td>
<td>2.6 - 3.5 K</td>
</tr>
<tr>
<td></td>
<td>Temperature Range (Single Cone)</td>
<td>2.6 - 20 K</td>
<td>2.6 - 20 K</td>
</tr>
<tr>
<td></td>
<td>Temperature Gradient</td>
<td>&lt; 3 μK</td>
<td>&lt; 1 μK</td>
</tr>
</tbody>
</table>
External Calibrator
External Calibrator
External Calibrator
Mission Operations

Taurus 3110

Simple table-driven operations
“Spin and Stare” science
PIXIE Samples Cosmic History

**Big Bang Cosmology** *
- Inflation
- GUT physics
- Quantum gravity

**Early Universe**
- Dark matter decay/annihilation
- Primordial density perturbations

**Reionization and First Stars** *
- Ionization history at end of Dark Ages
- Nature of first stars

**Large-scale Structure**
- Galaxy bias vs dark matter density
- Star formation at redshift 2--3

**Galactic Structure**
- Assembly history of the Galaxy
- Dust & chemical separation

* Specifically called out in Astro-2010 Decadal Survey
Primary Science: Inflation

GUT-Scale Physics: $r < 10^{-3}$ at $5\sigma$
- Detect $\sim$all large-field models
- Power spectrum to $l \sim 100$
- Reach limit of lensing foreground

Planck-Scale Physics: Map B-Mode Polarization
- Consistency relation $r = -6.2 \, n_t$
- Statistics of B-mode polarization field
Secondary Science: Inflation

Blackbody calibrator: Spectral distortions

Chemical potential $\mu = 1.4 \frac{\Delta E}{E}$

Energy release at $10^6 < z < 10^8$

PIXIE limit $\mu < 10^{-8}$

Silk damping of primordial perturbations

- Scalar index $n_s$ and running $\frac{d \ln n_s}{d \ln k}$
- Physical scale $\sim 1$ kpc ($1M_\odot$)

Daly 1991
Hu, Scott, & Silk 1994
Khatri, Sunyaev, & Chluba 2011
Secondary Science: Dark Matter
Blackbody distortion from dark matter decay or annihilation

Energy release at $10^6 < z < 10^8$

Chemical potential $\mu = 1.4 \frac{\Delta E}{E}$

Energy release $\Delta E \sim \Omega_{DM} \Gamma \Delta m$

Distort CMB from blackbody spectrum

PIXIE limit $\mu < 10^{-8}$
Reach cosmological limit $\tau < 3 \times 10^6$ sec
Test of gravitino dark matter

McDonald et al 2001
de Vega & Sanchez 2010
Feng 2010
Secondary Science: Reionization

Polarization: Optical depth ~ Electron density \( n(z) \)

Angular scale \( \leftrightarrow \) Horizon at redshift \( z \)

Spectrum: \( y \) distortion ~ Electron pressure \( \int nkT_e \)
- PIXIE limit \( y < 5 \times 10^{-9} \)
- Distortion must be present at \( y \sim 10^{-7} \)

**Same scattering for both signals:**
Combine to get \( n(z) \) and \( T_e \)
- \( T_e \) probes ionizing spectrum
- Distinguish Pop III, Pop II, AGN

Determine nature of first luminous objects

Hu & Holder 2003
Secondary Science: Cosmic Infrared Background

Thermal Dust Emission from $z \sim 1--3$
- Monopole: Galaxy Evolution
- Dipole: Bulk Motion
- Anisotropy: Matter power spectrum

Broad frequency coverage over CIB peak
- Complement Herschel, Planck

```
PIXIE noise is down here!
```

Knox et al. 2001
Fixsen & Kashlinsky 2011
Secondary Science: Interstellar Medium

400 Spectral Maps
Stokes I, Q, U
$\Delta \nu = 15 \text{ GHz}$

Continuum Emission
- Synchrotron, Dust

Line Emission
- CO, C+, N+, O, …

Dust Physics
- Silicate vs carbonaceous dust
- Large-scale magnetic field

Diffuse ISM
- Temperature, Density
- Energy Balance
- Metallicity

Extremely Rich Data Set!