SPIDER
Probing The Dawn Of Time
From Above The Clouds
See also SPIDER poster

Jon Gudmundsson

Adri Duivenvoorden

NORDITA
The Nordic Institute for Theoretical Physics
B-modes

- Thomson scattering within local quadrupole anisotropies generates linear polarization
- Scalar modes $\rightarrow$ T, E
- Tensor modes $\rightarrow$ T, E, B
- Ratio $r = \Delta T / \Delta S$
- Gravitational waves at LSS create B-mode polarization
- Probes Lyth bound of Inflation
- Ekpyrotic models $\rightarrow$ $r = 0$
Why is it so hard?

Polarization anisotropy
Planck X 2015

Synchrotron
CMB
Thermal dust

RMS brightness temperature (μK)

Frequency (GHz)
“Searches for microwave temperature anisotropies on various angular scales should be accompanied by attempts to determine polarization with comparable precision. The same area of sky should, if possible, be scanned at different wavelengths, in order to distinguish between primeval radiation and other contributions to the background with different spectra.”

-M. J. Rees
SPIDER: science goals

Measure cosmological B-modes on degree angular scales \textit{in the presence of foregrounds}

1) Verify angular spectrum
   (many uncorrelated bins out to large scales)

2) Verify frequency spectrum
   (multiple frequencies needed to separate foregrounds)

3) Verify statistical isotropy
   (large sky to check sub-regions)
# Platform summary

<table>
<thead>
<tr>
<th></th>
<th>Space</th>
<th>Balloon</th>
<th>Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>&gt;10-100x</td>
<td>1.5x</td>
<td>1x</td>
</tr>
<tr>
<td><strong>Max Mirror</strong></td>
<td>~8m</td>
<td>~2.8m</td>
<td>&gt;100m</td>
</tr>
<tr>
<td><strong>Max Payload</strong></td>
<td></td>
<td>3 tons</td>
<td></td>
</tr>
<tr>
<td><strong>Integration Time</strong></td>
<td>Years</td>
<td>Weeks</td>
<td>Indefinite</td>
</tr>
<tr>
<td>**Chance to fix/  **</td>
<td>~0</td>
<td>70%</td>
<td>100% (quickly)</td>
</tr>
<tr>
<td><strong>refly</strong></td>
<td>(in 1-2 years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Platform Reliability</strong></td>
<td>90%</td>
<td>85%</td>
<td>~100%</td>
</tr>
<tr>
<td><strong>Atmosphere</strong></td>
<td>None</td>
<td>~None</td>
<td>Can add noise</td>
</tr>
<tr>
<td><strong>FunFactor</strong></td>
<td>0.24</td>
<td>2.28</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**New Technology**
- needs SQ*
- careful, can bite but can SQ*
- easy

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*SQ = space qualification
Why ballooning?

- Balloon (95 kft)
- Airship (65 kft)
- SOFIA (41 kft)
- ALMA (0.5 mm PWV)

Transmission vs. Wavelength [μm]

Optical Loading vs. Frequency [GHz]

APRA 2016

Moriond 22/3/16

Lorenzo Moncelsi

Fraisse+ 2013
Why Ballooning?

- Avoid the atmosphere
  - Reduced $1/f \rightarrow$ access to larger scales

![Graph](Fraisse+ 2013)

**SPIDER:**
- $f_{HP} = 25$ mHz
- $f_{HP} = 50$ mHz
- $N_f^{-1}, f_{HP} = 50$ mHz

**BICEP**
- $B_{\ell}^2$
- $F_{\ell}$
- $F_{\ell}B_{\ell}^2$

Moriond 22/3/16
Long Duration Ballooning (LDB)

- The good:
  - Wider frequency windows
  - Fidelity to large angular scales
  - Space-like backgrounds → sensitivity

- The bad:
  - Mass/power constraints
  - Automation
  - Insane integration schedule
  - One shot at quality data
  - Recovery

- The ugly:
  - Government shutdowns...

- Why Antarctica?
  - Continuous solar power
  - Long flight times
  - Not Russian airspace

Moriond 22/3/16  Lorenzo Moncelsi
SPIDER Collaboration

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M.C. Runyan
A.D. Turner

[Logos and institutions' names]
SPIDER Overview

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky coverage</td>
<td>About 10 %</td>
</tr>
<tr>
<td>Scan rate (az)</td>
<td>4 deg/s at peak</td>
</tr>
<tr>
<td>Polarization modulation</td>
<td>Stepped cryogenic HWP</td>
</tr>
<tr>
<td>Detector type</td>
<td>Antenna-coupled TES</td>
</tr>
<tr>
<td>Multipole range</td>
<td>$10 &lt; \ell &lt; 300$</td>
</tr>
<tr>
<td>Observation time</td>
<td>16 days at 36km</td>
</tr>
<tr>
<td>Limits on $r$</td>
<td>0.03 (99% C.L.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>95</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescopes</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Bandwidth [GHz]</td>
<td>22</td>
<td>36</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>30-45%</td>
<td>30-50%</td>
</tr>
<tr>
<td>Angular resolution [arcmin]</td>
<td>42</td>
<td>30</td>
</tr>
<tr>
<td>Number of detectors (85% yield)</td>
<td>700</td>
<td>1300</td>
</tr>
<tr>
<td>In-band detector loading [pW]</td>
<td>$\leq 0.25$</td>
<td>$\leq 0.35$</td>
</tr>
<tr>
<td>NET per detector [$\mu$K·rts]</td>
<td>120-150</td>
<td>110-150</td>
</tr>
<tr>
<td>Instrument NET [$\mu$K·rts]</td>
<td>$\leq 6.5$</td>
<td>$\leq 5.1$</td>
</tr>
<tr>
<td>Projected 2015 depth [$\mu$K·arcmin]</td>
<td>12</td>
<td>10</td>
</tr>
</tbody>
</table>

(B2+Keck 150GHz = 3.0; Keck 95GHz = 7.6)
SPIDER: the instrument

• Lightweight, carbon fiber gondola frame and sun shields

• Largest cryogenic vessel on a balloon payload

• Reaction wheel + pivot for fast Az scanning

• Redundant pointing sensors for in-flight and post-flight attitude reconstruction
  - star cameras
  - dGPS
  - gyroscopes
  - pinhole sun sensors
  - magnetometer

• Nearly autonomous observations
Cryogenic System

- Lightweight (850 kg)
- 1300-L LHe4-only cryostat (4K)
- Two vapor cooled shields (30K, 120K)
- Capillary-fed 20-L superfluid LHe4 tank (1.5K)
- Closed-cycle He3 adsorption fridge per telescope (300mK)
- Two weeks from close up to cold detectors
- Baselined for a 20-day hold time

Gudmundsson+ 2010 & 2015
The Telescopes

- Focal Plane (300mK)
- A4K Optics Sleeve (1.6K)
- Cooled Black Lens (4K)
- Objective
- Copper-clad G-10 Wrap (4K)
- 4K Cold Plate
- A4K Spittoon (1.6K)
- Metal-mesh Filter (1.6K)
- Optical Stop (1.6K)
- Eyepiece Lens (4K)
- 4K Filters

References:

Runyan+ 2010
Filippini+ 2010

Moriond 22/3/16
• Sapphire with quartz (90 GHz) and Cirlex (150 GHz) bonded AR coatings
• Custom worm-gear mechanism turns at 4K
• Stepped twice daily to modulate polarization
• Last optical element: separates sky from internal systematics

Bryan+ 2010, 2016

Half-Wave Plates
95/150 GHz JPL detectors
285GHz NIST detectors

- platelet feedhorns: stack of precisely-aligned Si wafers, then gold-plate the whole assembly
- target $P_{\text{sat}} = \sim 3\text{pW}$
- AlMn ($T_c = 450\text{mK}$) & dirty Al films ($T_c = 1.6\text{K}$)
Observing Region

Rahlin+ 2014

\[ f_{\text{sky}} = \int \frac{d\Omega}{4\pi} \sqrt{\frac{N}{N_{\text{max}}}} \]

150 GHz, Full Flight

geometric \( f_{\text{sky}} = 11\% \)

hits-weighted \( f_{\text{sky}} = 6.3\% \)

Planck XXX 2014

Moriond 22/3/16

Lorenzo Moncelsi
This study suggests that without component separation, degree-scale polarized dust emission will limit the constraints of any experiment at or above the level of $r \sim 0.03$, even in the portions of the southern sky most free of Galactic dust emission.

- Foregrounds
  - Power spectra of $2^\circ$ sub-fields in SPIDER region

- Fraisse+ 2013
  - many sub-regions observed by SPIDER
  - “Southern Hole” is typical of other regions
  - significant dust contamination everywhere
  - synchrotron subdominant at our depths
launch day!
SPIDER: flight summary

- launched on 1/1/15
- all systems operational! (except dGPS)
- 16 days of science data
- $f_{\text{sky}} = \text{geometric 11\%, hits-weighted 6.3\%}$
- **1.5 TB** of data (analysis ongoing)


Moriond 22/3/16

Lorenzo Moncelsi
SPIDER: in-flight performance

- NETs in line with expectations
- Cosmic rays are not an issue
- But RFI is
- No obvious magnetic pick-up

### Total in-flight optical loading

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Frequency (GHz)</th>
<th>In-band power (pW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIDER</td>
<td>95</td>
<td>0.25</td>
</tr>
<tr>
<td>SPIDER</td>
<td>150</td>
<td>0.35</td>
</tr>
<tr>
<td>BOOMERanG</td>
<td>150</td>
<td>0.75</td>
</tr>
<tr>
<td>BICEP2</td>
<td>150</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Corresponding to a warm telescope emissivity of ~0.3% \( \epsilon \approx \frac{P_{\text{opt}}}{kT\Delta v} \) with \( T=250K \)

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SPIDER: temperature map
Published CMB Polarization (ground-based)

ACTpol (arxiv:1405.5524): 276 deg$^2$ $f_{\text{sky}} = 0.67\%$

PolarBear (arxiv:1403.2369): 24.5 deg$^2$ $f_{\text{sky}} = 0.06\%$

SPT 100d (arxiv:1503.02315): 100 deg$^2$

SPTpol 500d: 500 deg$^2$ $f_{\text{sky}} = 1.2\%$

Bicep/Keck (arxiv:1502.00643): 370 deg$^2$ $f_{\text{sky}} = 0.9\%$

2 years of data

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is SPIDER in the game?

Spider 2015: 4500 deg$^2$ \( f_{\text{sky}} = 11\% \)

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## Expected Sensitivity

<table>
<thead>
<tr>
<th>Band Center (GHz)</th>
<th>Bandwidth (GHz)</th>
<th>Beam FWHM (arcmin)</th>
<th>Number of Spatial Pixels</th>
<th>Number of FPU per flight</th>
<th>Detector Sensitivity ($\mu K_{CMB}\sqrt{s}$)</th>
<th>FPU Sensitivity ($\mu K_{CMB}\sqrt{s}$)</th>
<th>Instrumental Sensitivity ($\mu K_{CMB}\sqrt{s}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>94</td>
<td>21</td>
<td>42</td>
<td>144</td>
<td>1 (3)</td>
<td>166</td>
<td>11.4 [10]</td>
<td>6.5 (652)</td>
</tr>
<tr>
<td>150</td>
<td>33</td>
<td>28</td>
<td>256</td>
<td>2 (3)</td>
<td>164</td>
<td>8.8 [7]</td>
<td>5.1 (1030)</td>
</tr>
<tr>
<td>285</td>
<td>67</td>
<td>16</td>
<td>256</td>
<td>3 (−)</td>
<td>335</td>
<td>15</td>
<td>8.7</td>
</tr>
</tbody>
</table>

250 **JPL** broad-band 20 256 1? (−) TBD TBD TBD

Planck 2015  BICEP1 QUIET-Q QUaD
WMAP 9yr BICEP2 QUIET-W

**APRA 2016**

**Lorenzo Moncelsi**
Expected Sensitivity

- Dec 2014: 3x (90 GHz, 150 GHz)
  - $r<0.03$ (99% CL) without FG
- Dec 2017: 2x (90 GHz, 150 GHz, 285 GHz)
  - $r<0.03$ (99% CL) with FG

BK14 w/ 95GHz 2016

With foregrounds
- No foregrounds

Fraisse+ 2013

Planck
- SPIDER 1
- SPIDER 2
SPIDER: recovery

Heroes: Ed Young & British Antarctic Survey
new cryostat built, now under test!

BK14 w/ 95GHz 2016

- foreground-optimized channel: **285 GHz**
- very hard to observe from the ground
- $r < 0.03$ (3σ) with foregrounds
- successful recovery, planned for Dec 2017

Moriond 22/3/16
SPB: New opportunities
Stay Tuned!

Cape Bird
Cape Royds
Erebus Ice Tongue
Hut Point Peninsula
Black Island
McMurdo Ice Shelf
Mt. Erebus
Windless Bight
Mt. Terror
Cape Crozier
White Island