CMBPol: Testing Inflation with Space-Borne Measurements of CMB Polarization

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Scott Dodelson (FNAL)
Shaul Hanany (U. Minnesota)
Steve Meyer (U. Chicago)

Representing
The Primordial Polarization Program Definition Team
The CMB Inflation Probe Astrophysics Strategic Mission Concept Study
The EPIC-IM Mission Study Team

Astro2010, Pasadena, 8 June 2009
The EPIC-IM Study Team

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Adrian Lee  UC Berkeley
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PPDPT

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CMB Inflation Probe ASMCS

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Lyman Page  Princeton U.
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Decadal White Papers

The Origin of the Universe as Revealed Through the Polarization of the CMB, Dodelson et al. and 211 Co-signers
Observing the Evolution of the Universe, Page et al. and 168 Co-signers
A Program of Technology Development and Sub-Orbital Observations of CMB Polarization Leading to and Including a Satellite Mission, Meyer et al. and 141 Co-signers

CMB Community Reports

Theory and Foregrounds:  5 Papers with 135 Authors and Co-Authors
   Probing Inflation with CMB Polarization, Baumann et al. 2008, ArXiv 0811.3919
   Gravitational Lensing, Smith et al. 2008, ArXiv 0811.3916
   Reionization Science with the CMB, Zaldarriaga et al. 2008, ArXiv 0811.3918
   Prospects for Polarized Foreground Removal, Dunkley et al. 2008, ArXiv 0811.3915
   Foreground Science Knowledge and Prospects, Fraisse et al. 2008, ArXiv 0811.3920
Systematic Error Control:  10 Papers with 68 Authors and Co-Authors

CMB Technology Development:  22 Papers with 37 Authors and Co-Authors

Mission Study Reports

The Experimental Probe of Inflationary Cosmology, Bock et al. 2008, ArXiv 0805.4207

See  http://cmbpol.uchicago.edu  for a full compilation
Key Inflationary Observables
1. Nearly scale-invariant fluctuations
2. Flat universe
3. Adiabatic fluctuations
4. Nearly Gaussian fluctuations
5. Super horizon fluctuations
6. Departure from scale invariance?
7. Non-Gaussianity?
8. Inflationary gravitational waves?

First Definitive CMB Result
- Nearly scale-invariant fluctuations: COBE
- Flat universe: Boomerang + Maxima + TOCO
- Adiabatic fluctuations: Boomerang + Maxima + WMAP
- Nearly Gaussian fluctuations: WMAP
- Super horizon fluctuations: WMAP
- Departure from scale invariance?: Planck
- Non-Gaussianity?: Planck
- Inflationary gravitational waves?: CMBpol

Comprehensively measure inflationary CMB polarization signal corresponding to inflation at GUT energy scales
CMB Community Reports

*Probing Inflation with CMB Polarization*, Baumann et al. 2008, ArXiv 0811.3919
*Gravitational Lensing*, Smith et al. 2008, ArXiv 0811.3916
*Reionization Science with the CMB*, Zaldarriaga et al. 2008, ArXiv 0811.3918
*Prospects for Polarized Foreground Removal*, Dunkley et al. 2008, ArXiv 0811.3915
*Foreground Science Knowledge and Prospects*, Fraisse et al. 2008, ArXiv 0811.3920
Science Objectives for a Space Mission

CMB Community Reports

- Probing Inflation with CMB Polarization, Baumann et al. 2008, ArXiv 0811.3919
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Measure Inflationary B-mode spectrum at $r = 0.01$ to astrophysical limits

- GUT energy scale
- Large field inflation
- $n_t / r$ consistency test
Science Objectives for a Space Mission

Measure Inflationary B-mode spectrum at $r = 0.01$ to astrophysical limits

- Neutrino mass hierarchy
- Dark energy at $z > 2$

Measure B-mode cosmic shear spectrum to cosmic limits

- GUT energy scale
- Large field inflation
- $n_t / r$ consistency test

CMB Community Reports

- Probing Inflation with CMB Polarization, Baumann et al. 2008, ArXiv 0811.3919
- Gravitational Lensing, Smith et al. 2008, ArXiv 0811.3916
- Reionization Science with the CMB, Zaldarriaga et al. 2008, ArXiv 0811.3918
- Prospects for Polarized Foreground Removal, Dunkley et al. 2008, ArXiv 0811.3915
- Foreground Science Knowledge and Prospects, Fraisse et al. 2008, ArXiv 0811.3920
Science Objectives for a Space Mission

- Measure E-mode spectrum to cosmic variance to damping tail
  - Precision cosmology
  - Departure from scale inv.
  - Reionization history

- Measure B-mode cosmic shear spectrum to cosmic limits
  - Neutrino mass hierarchy
  - Dark energy at $z > 2$

- Measure Inflationary B-mode spectrum at $r = 0.01$ to astrophysical limits
  - GUT energy scale
  - Large field inflation
  - $n_t / r$ consistency test

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Science Objectives for a Space Mission

- Measure inflationary B-mode spectrum at \( r = 0.01 \) to astrophysical limits
- Measure E-mode spectrum to cosmic variance to damping tail
- Measure B-mode cosmic shear spectrum to cosmic limits
- Map Galactic magnetic fields via dust polarization
- Measure inflationary B-mode spectrum at \( r = 0.01 \) to astrophysical limits

CMB Community Reports

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- Foreground Science Knowledge and Prospects, Fraisse et al. 2008, ArXiv 0811.3920
The EPIC-IM Concept in a Nutshell

Experimental Probe of Inflationary Cosmology – Intermediate Mission

1.4 m Crossed Dragone Telescope
- resolution to measure lensing and E-modes to cosmic limits
- wide FOV for sensitivity
- low polarization and sidelobes

Large Focal Plane
- high sensitivity for Inflationary B-modes
  equates to 3600 Planck missions!
- wide band coverage for foregrounds
- high frequencies for Galactic science

Cooling system
- Maximal use of passive cooling
- Efficient 4 K cryocooler (~MIRI)
- Continuous 100 mK cooler (~Planck)

L2 Halo Orbit
- scan strategy for large-scale polarization
- extremely stable thermal environment
- requires sunshield
- simple operations, conventional spacecraft

Resources similar to the Planck satellite mission

Further Information Available:
The Experimental Probe of Inflationary Cosmology, Bock et al. 2008, ArXiv 0805.4207
Path to CMBPol: Upcoming Measurements of CMB Polarization, Chicago, 1-3 July 2009
All Sky Maps of Projected Gravitational Potential

Gravitational potential determined from CMB polarization and temperature maps

Potential sensitive to
- neutrino masses
- late dark energy

All-sky potential map: 600 of these maps on the whole sky!
- a legacy for every future study of structure formation
Mapping Galactic Magnetic Fields over the Whole Sky

Map of full sky with $\sigma_p < 0.3\%$

<table>
<thead>
<tr>
<th>Mission</th>
<th>Band GHz</th>
<th>FWHM arcmin</th>
<th>$\sigma(Q)$ kJy/sr/beam</th>
<th>Pol. depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck</td>
<td>350</td>
<td>5</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>EPIC</td>
<td>500</td>
<td>2</td>
<td>0.9</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>850</td>
<td>1</td>
<td>0.7</td>
<td>0.01</td>
</tr>
</tbody>
</table>

How does large-scale Galactic field related to field in embedded star-forming regions?
Q1: “What are the details of how the ground and suborbital programs lead to the space mission?”
How Sub-Orbital Program Benefits a Satellite Mission

**Historical Interplay:** Suborbital Experiments serve to

- Shape scientific objective of a space mission
- Develop experimental methodologies
- Train leaders of future orbital missions
- Develop technologies at **systems level**

**Satellite Mission**

**Sub-Orbital Precursor**

**COBE**
1989

**WMAP**
2001

**Planck**
2009

**CMBPOL**
2022

**Sensitivity**

- **COBE**
  - 100 $\mu$K

- **WMAP**
  - 1 $\mu$K

- **Planck**
  - 100 nK

- **CMBPOL**
  - few nK

**Multiple**

Ground-based & Balloon-borne

**Archeops, Boomerang, Maxima**

**QMAP, SK, TOCO**

**U2-DMR**

**Woody-Richards**
Technology Needed for Space: An Evolution from Planck

1.5 m Telescope
3-stage V-groove
4 K Cooler
100 mK Cooler
Polarized bolometer
100 mK Focal Plane

Planck Heading to L2!

CMB Community Workshop:
Technology Development for a CMB Probe of Inflation, Boulder CO, 25-28 August 2008
Rapid Progress in Detector Development

- Rapid progress in arrays
- Development synergy with far-IR and X-ray astronomy
Sub-Orbital Predecessors to EPIC-IM Focal Plane

- Much larger $A\Omega$ and sensitivity than any planned sub-orbital experiment
- Sub-orbital platforms demonstrating technology options

$T_0 = 100$ mK
$N_{det} = 11,094$
9 Bands

Technology & Sub-Orbital Program

Optical Coupling
Feed Coupled

Detector / Readout
Time-Domain SQUID

Freq-Domain SQUID

Planar Antennas

Lens-Coupled Antennas

RF-Muxed MKID

• 30 GHz
• 45 GHz
• 70 GHz
• 100 GHz
• 150 GHz
• 220 GHz
• 340 GHz
• 500 GHz
• 850 GHz

1.5 m

$T_0 = 100$ mK
$N_{det} = 11,094$
9 Bands
Transition from Sub-Orbital Experiments to Space


Current Sub-Orbital and Ground-Based Experiments

<table>
<thead>
<tr>
<th>US Balloons</th>
<th>US Ground-based</th>
<th>European Ground-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBEX</td>
<td>ACT</td>
<td>BRANE</td>
</tr>
<tr>
<td>SPIDER</td>
<td>MBI</td>
<td>QUIJOTE</td>
</tr>
<tr>
<td>PIPER</td>
<td>QUIET</td>
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<tr>
<td>ABS</td>
<td>BICEP2</td>
<td></td>
</tr>
<tr>
<td>Keck Array</td>
<td>Poincare</td>
<td></td>
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<tr>
<td>PolarBeaR</td>
<td>SPT</td>
<td></td>
</tr>
</tbody>
</table>

Vigorous ‘Market-Driven’ Scientific Niches
- Wide variety of technologies
- Wide range of frequencies, resolution, and sky coverage
- Diverse approaches to systematic error control
Transition from Sub-Orbital Experiments to Space


<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Maps of Temperature</td>
<td>WMAP</td>
<td>PLANCK</td>
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</tr>
<tr>
<td>Polarization Sensitivity</td>
<td>100μK-s%^{}</td>
<td>10μK-s%^{}</td>
<td>10μK</td>
<td>1μK-s%^{}</td>
<td>0.1μK</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Polarization Systematic Limit</td>
<td>1μK</td>
<td>0.1μK</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Polarization Map Sensitivity 1 x 1 degree</td>
<td>1μK</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Where we are today</td>
<td></td>
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</tr>
</tbody>
</table>

Current Sub-Orbital and Ground-Based Experiments

**US Balloons**
- EBEX
- SPIDER
- PIPER

**US Ground-based**
- ABS
- Keck Array
- PolarBeaR
- ACT
- MBI
- QUIET

**European Ground-based**
- BICEP2
- Poincare
- SPT
- BRAIN
- QUIJOTE

Vigorous ‘Market-Driven’ Scientific Niches
- Wide variety of technologies
- Wide range of frequencies, resolution, and sky coverage
- Diverse approaches to systematic error control
Recent Measurements of CMB Polarization

\[
\ell(\ell+1)C_\ell / 2\pi [\mu K^2]
\]

Chiang et al. 2009, arXiv 0906.1181 & 1003

Multipole \( \ell \) vs. \( \ell(\ell+1)C_\ell / 2\pi [\mu K^2] \) for different experiments.
High Fidelity Separation of E and B

- Map sensitivity = 0.5 $\mu$K / sq. degree
- Systematic errors << noise
- No E/B mixing

Chiang et al. 2009, arXiv 0906.1181
Scientific Transition from Sub-Orbital to Space

Sub-Orbital Program Optimized to Detect Inflationary Polarization Signal

Most methods use deep searches on small patches of sky
- Most experiments are targeting $\ell = 100$ peak
- Expect detections or upper limits to $r \sim 0.05$ in limited $\ell$ range in 5 years

Satellite Designed for Comprehensive Measurements of CMB Polarization

Measures the entire sky to fundamental limits
- Entire Inflationary B-mode spectrum to astrophysical limits
- Lensing and E-mode signals to cosmological limits
### Why is Space Necessary?

**EPIC-IM Designed to Measure Polarization Spectra to Fundamental Limits**

<table>
<thead>
<tr>
<th>Science Objective</th>
<th>Attribute</th>
<th>Why Space is Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure Inflationary B-mode spectrum for $2 &lt; \ell &lt; 200$</td>
<td><strong>All-Sky Coverage</strong></td>
<td>High fidelity measurements of low spatial multipoles</td>
</tr>
<tr>
<td>Remove foregrounds to measure $r = 0.01$ to astrophysical limits</td>
<td><strong>Frequency Coverage</strong></td>
<td>Full access to the electromagnetic spectrum without degradation from Earth’s atmosphere</td>
</tr>
<tr>
<td>Measure E-mode and lensing B-mode to cosmological limits</td>
<td><strong>Sensitivity</strong></td>
<td>Large improvement due to lower backgrounds, large system throughput, longer integration time</td>
</tr>
<tr>
<td>Measure Inflationary B-mode spectrum to astrophysical limits</td>
<td><strong>Systematic Error Control</strong></td>
<td>Superior control, stability, redundancy, and monitoring of systematic errors</td>
</tr>
</tbody>
</table>

- **Primary Science Objective**
- **Secondary Science Objective**
Transitioning from Sub-Orbital Program to Space

**Mission Planning**
- Space systems design
- Set technology needs

**Technology Development**
- Center funding for arrays
- $1M/yr University directed

**Theory**
- Lensing, foregrounds, models

**Balloon Experiments**
- Technology implementation
- Systems development
- ‘Science-market’ driven

**Ground-Based Experiments**
- Technology implementation
- Systems development
- ‘Science-market’ driven

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**Satellite funding wedge not shown**

These cost profiles are notional and have not been negotiated with or agreed to by NASA HQ, the NSF, or the NIST
Q3: “What aspects of the program need to continue during/after the space mission?”
Programs to Continue After Mission Start

• **Theory program should continue**
  Supports investigations useful to satellite program

• **Technology for satellite borne by mission funding**

• **Expect CMB B-mode polarization experiments will taper down**
  But: Let scientific marketplace decide

*Examples of reasons for a continued level of experiment funding:*
- Complementary polarization experiments
  - Foreground measurements at low frequencies
  - High resolution polarization experiments

- Sub-orbital demonstration of satellite-specific technologies
  - Buys down risk. Very successful in the past

- **CMB temperature experiments**
  - High-resolution ground-based observations
  - Absolute spectrum experiments

- Experiments we can’t foresee today
Q2: “What metrics are used to determine that the program has achieved enough to proceed with a space mission?”
Evaluation for Start of Satellite Program in 2015

Expected State of CMB Polarization in 2015

Scientific
- Lensing BB signal detected
- Either Inflationary B-modes detected,
  Case for satellite start very compelling in 2015
- Or upper limit to $r \lesssim 0.05$
  Reassess role for satellite in 2015

We are not recommending a fixed metric for a satellite start. We are recommending a 2015 evaluation for a satellite start.

Foregrounds
- Measured in deep regions from ground & balloons
- Measured over entire sky by Planck
- Subtraction tested both deep and shallow

Technology readiness
- Focal plane arrays to TRL = 6

Systematic error control
- Polarization effects, $E \rightarrow B$ conversion, etc.

Field will be ready to transition to a satellite experiment mid-decade, fully armed with scientific case and demonstrated technology

We recommend:
1) Funding the program proposed in white paper through 2015
2) External evaluation in 2015 of case for satellite start
Backup Materials
## EPIC-IM Summary

### Launch Configuration

<table>
<thead>
<tr>
<th>Optics</th>
<th>1.4 m wide-field crossed Dragone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>Sun-earth L2 halo</td>
</tr>
<tr>
<td>Mission Life</td>
<td>4 years</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>Atlas V 401</td>
</tr>
<tr>
<td>Detectors</td>
<td>11094 TES bolometer or MKID detectors</td>
</tr>
<tr>
<td>Bands</td>
<td>30, 45, 70, 100, 150, 220, 340, 500 &amp; 850 GHz</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.9 mK arcmin; 3600 Planck missions</td>
</tr>
<tr>
<td>Spacecraft</td>
<td>3-axis commercial</td>
</tr>
<tr>
<td>Data Rate</td>
<td>7.7 Mbps</td>
</tr>
</tbody>
</table>

### Deployed Configuration

<p>| Total Delta-V           | 170 m/s                          |
| Payload Power           | 440 W (CBE)                      |
| Spacecraft Power        | 533 W (CBE)                      |
| Total Power             | 1392 W (w/ 43 % cont.)           |
| Payload Mass            | 813 kg (CBE)                     |
| Spacecraft Mass         | 584 kg (CBE)                     |
| Total Mass              | 2294 kg (w/ 43 % cont.)          |
| Vehicle Margin          | 1287 kg (36 %)                   |
| Cost                    | $920M FY09                       |</p>
<table>
<thead>
<tr>
<th><strong>EPIC</strong>-<strong>Low Cost</strong></th>
<th><strong>Intermediate Mission</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Science</strong></td>
<td>Inflationary B-mode polarization only</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>500 Plancks</td>
</tr>
<tr>
<td><strong>Detectors</strong></td>
<td>2400</td>
</tr>
<tr>
<td><strong>Aperture</strong></td>
<td>Six 30 cm refractors</td>
</tr>
<tr>
<td><strong>Bands</strong></td>
<td>30 – 300 GHz</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>LHe cryostat + ADR</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>1320 kg CBE</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$660M (FY07)</td>
</tr>
</tbody>
</table>
If Planck or suborbital experiments detect B-modes at $r \geq 0.01$, a low-cost option would be possible. + Knowledge of foregrounds may permit more limited frequency coverage

- Same telescope, orbit, and scan strategy as EPIC
- Similar mass and size $\Rightarrow$ same rocket
- Key differences:
  - Based on amplifiers at 20 K
  - Total power, including cooler, $\sim 2$ kW, so solar panel much larger

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Power [mW]</th>
<th>$T_{\text{sys}}$ [K]</th>
<th>NEQU [$\mu$K s$^{1/2}$]</th>
<th>NEQU/freq [$\mu$K s$^{1/2}$]</th>
<th>$Q, U$ Noise/2 deg$^2$ 4-yr [nK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>4</td>
<td>4</td>
<td>10</td>
<td>81.6</td>
<td>40.8</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
<td>7</td>
<td>11</td>
<td>87.0</td>
<td>12.3</td>
</tr>
<tr>
<td>70</td>
<td>160</td>
<td>10</td>
<td>13</td>
<td>77.7</td>
<td>6.1</td>
</tr>
<tr>
<td>100</td>
<td>75</td>
<td>12</td>
<td>15</td>
<td>75.0</td>
<td>8.7</td>
</tr>
<tr>
<td>150</td>
<td>75</td>
<td>15</td>
<td>23</td>
<td>93.9</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Total $N = 364$, Total power dissipated $= 4$ W
CMB Community Workshop: 
*Mitigating Systematic Errors In Space-Based CMB Polarization Measurements* 
Annapolis MD, 28-30 June 2008
Measuring Low Multipoles in Space-Borne Observation

CMB Community Workshop:
Mitigating Systematic Errors In Space-Based CMB Polarization Measurements
Annapolis MD, 28-30 June 2008
Ideal Scan Strategy for All-Sky Polarization Measurement

N-hits (1-day)

Angular Uniformity* (6-months)

Planck

WMAP

EPIC

*<cos^2 \beta + <sin^2 \beta>^2
# Technology Plan for CMBPOL

## Tech. Needs

<table>
<thead>
<tr>
<th>Detector Arrays</th>
<th>Current State of the Art in 2009</th>
<th>Implementation by 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES + SQUID TDM</td>
<td>Option 1. 11,000 detectors NEP = 3 aW/Hz, 1/f knee &lt; 8 mHz</td>
<td>KECK &amp; SPIDER TES + SQUID TDM, planar antenna</td>
</tr>
<tr>
<td>TES + SQUID FDM</td>
<td>Option 2. 10,000 detectors NEP = 2 aW/Hz, 1/f knee &lt; 50 mHz</td>
<td>POINCARE, ABS, SPTPOL TES + SQUID TDM, feed + antenna</td>
</tr>
<tr>
<td>MKID + RF Mux</td>
<td>Option 3. 1000 detectors NEP = 1 aW/Hz, 1/f knee &lt; 1 Hz</td>
<td>POLARBEAR TES + SQUID FDM, lens + antenna</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cooling to 100 mK</th>
<th>Option 1. Astro-E2 ADR: TRL = 9, single-shot</th>
<th>Technology + sub-orbital program, implementation to TRL ≥ 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 µW @ 100 mK</td>
<td>Planck CCO: TRL = 9, 1 µW @ 100 mK</td>
<td>MKIDCAM MKID + RF Mux, planar antenna</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cooling to 4 K</th>
<th>Option 1. Planck V-grooves: TRL = 9</th>
<th>Mission planning program: space-specific designs with highTRL components</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 mW @ 4 K</td>
<td>JWST/MIRI: 6 K cooler: TRL = 5-9</td>
<td>Continuous ADR, closed cycle DR</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Option 1. QUIET: Crossed Dragonne, Planck: 1.5 m CFRP, Herschel: 3.5 m SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14 m λ &gt; 350 µm</td>
<td>QUIET, Planck, Herschel</td>
</tr>
</tbody>
</table>

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<tr>
<th>Sunshield</th>
<th>Option 1. JWST: 5 shields, 22 x 12 m deployed, Component TRL = 9, Design TRL = 3-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 shields</td>
<td>JWST sunshield, 12 x 16 m</td>
</tr>
</tbody>
</table>

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