Technology Needs for Space-Based Cameras and Spectrometers

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NASA/GSFC
Abstract

Future: cooled, large aperture, low background telescopes. Instruments will image large areas & accept broad spectral coverage.

Large area imaging requires:
- Large format arrays of direct detectors
- Careful optical design
- Spectral coverage and/or polarimetry

Direct detection spectrometers require:
- Detectors orders of magnitude more sensitive
- Clever optical designs

Instrument technologies will enable:
- Survey missions (Explorer- and Probe-class)
- Observatory-class missions SAFIR and SPECS
Instrument Technology

Outline

• Imaging:
  – Parameters
  – Present/Future Instruments
  – Desired Performance

• Spectroscopy:
  – Parameters
  – Detectors

• Future Missions SAFIR/SPECS
Instrument Technology

Outline

- **Imaging:**
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- **Spectroscopy:**
  - Parameters
  - Detectors
- **Future Missions SAFIR/SPECS**
Imaging Overview

- Imaging is the first capability required by new facilities
- Wide-field imaging permits:
  - Surveys
  - Studies of large fields of view
  - Control of drifts / systematics

Simulation of galaxies as observed with SAFIR at 200/350/450μm.
The Power of Large Arrays

350μm ground-based (CSO/SHARC II)

DR21 with IRAC (upper) and MIPS (lower)
Scientific Needs

- High Sensitivity
- Broad wavelength coverage
- Sufficient angular resolution
- Dynamic Range
- Imaging Speed
Scientific Needs

- High Sensitivity
- Broad wavelength coverage
- Sufficient angular resolution
- Dynamic Range
- Imaging Speed
- Cold telescope
- Good detectors
- Filters / mechanisms
- Multiple arrays
- Large aperture
- Good optical design
- Good detectors
- Lots of good detectors
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<td>• Imaging Speed</td>
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<tr>
<td>• Is cold feasible?</td>
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<tr>
<td>• What is <em>required</em>?</td>
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<tr>
<td>• How much is enough?</td>
</tr>
<tr>
<td>• What sources will we look for?</td>
</tr>
<tr>
<td>• Can we generate a compelling science case to enable a long-term detector program?</td>
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</table>
Angular Extent?
Angular Resolution?

Spitzer  SAFIR  ~100m
Wavelength Coverage

- What is the wavelength range?
- How many wavelengths?
- Simultaneous imaging
  - Dichroic optical relay
  - Adjacent fields of view
  - Filter changer

Deep galaxy field with Herschel/SPIRE-like instrument (highlighted colors)
Importance of Image Fidelity

Kuchner et al. model of ε Eri;
40-100μm wavelengths
Interferometer Image Fidelity

Resolving out structure can be a killer for certain projects...

(figure courtesy of Stephen Rinehart)
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Covers 3 wavelengths; FOV of several arcmin (e.g., 2.6′ x 5.2′ at 70μm); spectrometer too!
Features:

- Dichroic for simultaneous observing at two wavelengths over 2.3’ x 4.6’ FOV.

- Two identical modules provide redundancy against failure.

- Each module’s dual filter wheels include wavefront sensing hardware.
Features:

- **Broad-band Imaging**
  - $5 < \lambda < 27 \, \mu m$
  - $1.7' \times 1.7' \, FOV$
- **R=3000 Integral Field**
  - $3'' \times 3'' \, FOV$
  - 2 channels
    - $5 < \lambda < 10 \, \mu m$
    - $10 < \lambda < 27 \, \mu m$
- **R = 100 Slit**
  - $5 < \lambda < 10 \, \mu m$
Herschel / SPIRE
U. Cardiff – M. Griffin

Imaging photometer:
- simultaneous observation in 3 bands at 250, 350, 500 μm
- Field of view 4’ x 8’

Imaging FTS:
- Covers 200-670μm
- Field of view 2.6’
- Spectral resolution ~300km/s
Photometry mode:
- Simultaneous imaging in two bands, 75μm/170μm or 110μm/170μm
- Field of view 1.75’ x 3.5’

Spectroscopy mode:
- 50” x 50” FOV
- Instantaneous spectral coverage of ~ 1500 km/s
Features:

- Covers 50-215μm in 4 bands
- Scale-changing optics carousel; always diffraction-limited
- FOV of ~arcmin (e.g., 1.2’x3.2’ at 155μm)
Features:

- Covers 100-645\(\mu\)m with imaging
- Double Fabry-Perot to provide resolution of \(\sim250\text{km/s}\)
- FOV of \(\sim\text{arcmin}\) (e.g., 1’x3’ at \(\sim200\mu\text{m}\))
Features:

- Covers 50-200μm in 4 bands
- Scans whole sky
- FOV of ~10 arcmin
Einstein Inflation Probe (CMBPol):
- 1-3mm imaging
- Large field of view
- Polarimetric
- All-sky survey, redundant coverage

WISE:
- 3.5-23μm imaging
- ~1° FOV
- All-sky
Origins Probes

- **Galactic Life Cycle Observer** *(Dowell et al. poster)*; polarimetric imaging & C+ spectroscopy of Galaxy
- **Background-Limited IR/Submm Spectrograph** *(BLISS; NASA/JPL)*; high sensitivity broadband spectrometer for SPICA
- **Survey of Infrared Cosmic Evolution** *(SIRCE; NASA/GSFC)*; all-sky high resolution 50-850µm sky survey
- **Space Infrared Interferometric Telescope** *(SPIRIT; NASA/GSFC)*; direct-detection interferometer
- **CALISTO** *(NASA/JPL)*; imaging spectrometry w/FTS & grating
- **Space Terahertz Observatory** *(STO; Walker et al. poster)*; high spectral resolution large single aperture
- **SPECIES** *(Pearson et al. poster)*; high spectral resolution interferometer
BLAST

- Balloon-borne 2-meter carbon fiber telescope
- Simultaneous imaging at 250, 350, 500 μm.
- Beam size 30, 41, 59”
- Field of view: 6.5’ x 13’
BLAST Cold Re-imaging Optics

250 μm
350 μm
500 μm
Instrument Technology

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SAFIR Instrument Complement

From Harvey et al. (2002); Amato et al. (2002)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>$\lambda$ range</th>
<th>Format &amp; Type</th>
<th>Sensitivity</th>
<th>Availability*</th>
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<td>Camera</td>
<td>20 - 600$\mu$m</td>
<td>128x128 Bolometers</td>
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<td>Small Array Heterodyne Mixers</td>
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<td>Sensitivity ~few years Format ~few years</td>
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Low Resolution Requirements

Camera

$\lambda/\Delta\lambda \sim 100$
How Important Cold Is

Sensitivity of R=1000 spectrometer to telescope temperature

How much photon noise hurts with a warmer telescope: continuum or spectroscopic
Polarimetric Imaging

Scientifically:

- In Galaxy, trace magnetic fields in star formation regions, etc.

- CMB Polarization traces early Universe
Polarimetric Imaging

Options:

- Modulate polarization with refractive optics
  - or -
- Modulate polarization with reflective optics
  - or -
- Just spin the instrument

- Direct imaging with multiple arrays
  - or -
- Polarimetric Array
Radiation Coupling

- Technique for power absorption is a design choice dictated by the application
  - Resistive absorber
    - Instrument optics limits $A\Omega$
  - Concentrators
    - Multimode (e.g., Winston Cones)
    - Single mode (e.g., Feedhorn or planar antenna)
- Calculations of optical coupling can be done reliably, and provide excellent basis for design
Multi-Color Bolometer Arrays

SPEED & EDGE instruments:
(NASA/GSFC, U. Chicago, U.C. Davis, U. Massachusetts, and U. Wisconsin)

- Compact
- Simultaneous spatial and spectral information
- Efficient
- Horn-coupled
- Diffraction-limited at $\lambda=2.1$ mm

(courtesy G. Wilson)
Instrument Technology

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High Resolution Requirements

$\frac{\lambda}{\Delta \lambda} \approx 1000$

$\frac{\lambda}{\Delta \lambda} \approx 10^6$
Spectrometer Sensitivities

SAFIR Background Limited Detector Requirements

Photometry: 25% bandwidth, 2 polarizations, 50% transmission

Spectroscopy: R=1000, single polarization, 25% transmission

Temperature Dependence of SAFIR Sensitivity

^ Requirements on Detectors
Achievable sensitivity -->
Whither Spectroscopy?

Science wants spectral resolutions of better than $\sim300\text{km/s}$ for galaxies; better than $30\text{km/s}$ for Galaxy

How do you produce an efficient spectrometer? How do you image simultaneously?

Dispersive:
- physically large
- limited wavelength range

Interferometric:
- lower efficiency
- slower (throw away photons)
- can be large and/or mechanically complex

Heterodyne:
- limited sensitivity ("quantum penalty")

Energy Resolving:
- detect all photons all the time!
Whither Spectroscopy?

Science wants spectral resolutions of better than ~300 km/s for galaxies; better than 30 km/s for Galaxy

How do you produce an efficient spectrometer? How do you image simultaneously?

Dispersive:
- Grating – big; limited tunable bandwidth; hard 2D imaging
- Grating+FTS – low spectral resolution; poor 2D imaging

Interferometric:
- FTS – low sensitivity from loading; slow
- Fabry-Perot – low optical efficiency; slow; dual elements
- FP+FTS – low optical efficiency; slow

Heterodyne:
- poor sensitivity “quantum penalty”

Energy-Resolving:
- technologically immature

(Ferlet & Swinyard poster)
Sensitivity is best for direct detection spectrometers if:

1. Photon occupation number is small
2. Don’t have to spend lots of time to get all information
3. Detectors are good enough

Coherent vs. Direct Detection

Assumptions:

- $\eta_d^c = 0.5$
- $\eta^c = 0.1$

- $10^{-1}$
- $10^{-2}$
- $10^{-3}$

- $10^0$
- $10^1$

Background occupation number $(n_0)$

- 15 K
- 80 K
- 40 K

- 30 channel scan
- HSO at 1 THz ($\varepsilon = 0.04$)
- SOFIA 0.5 - 2 THz
- mm/submm ground

- Space telescope at 1 THz ($\varepsilon = 0.02$)

Zmuidzinas 2002
Instrument Technology

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Even with quantum noise, SAFIR (or STO!) can surpass other facilities at 100-300μm.
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<td><strong>Experiment</strong></td>
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<td>Ground-based cameras</td>
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<tr>
<td>e.g. SHARC II; BOLOCAM; SCUBA-2</td>
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Examples of Detector Arrays

- **Spitzer/MIPS**
  - 100 Element Flight Array
  - (U. of Arizona)
  - 160μm

- **SOFIA/HAWC**
  - 384 Element Flight Array
  - (GSFC)
  - 50-450μm

- **Herschel/SPIRE**
  - 144 Element Prototype Array
  - (Caltech/JPL)
  - 200-1000μm
Detector Choice

Photoconductor (Semiconductor or superconductor based):

Bolometer (Thermistor is semiconductor or superconductor based):
Conventional Bolometers

- Most devices use semiconductor processing techniques to produce $G = dP/dT$
- $G = G_0 T^n; \ G_0 \sim 3 \cdot 10^{-10} \ \text{W/K}^{n+1}$
- Without expensive investment or smarter technology, we’re limited!
- To achieve:
  - $10^{-16} \ \text{W/Hz} \quad \text{--} \quad T_C = 2K$
  - $10^{-17} \ \text{W/Hz} \quad \text{--} \quad T_C = 0.6K$
  - $10^{-19} \ \text{W/Hz} \quad \text{--} \quad T_C = 0.07K$
  - $10^{-20} \ \text{W/Hz} \quad \text{--} \quad T_C = 0.024K$
Choices, choices...

1. Photoconductors and tunnel junction detectors
   - BIB Ge and GaAs photoconductors w/ JFET CIA
   - Quantum dot photoconductor w/ quantum dot SETs
   - Long-wavelength QWIP detectors
   - SQPT photoconductor w/ RF SET
   - KID direct detector (couple radiation directly)
   - SIS/STJ detectors
   - HEB/SIS mixers w/ HEMTs

2. Multiplexable bolometers
   - Transition Edge Superconductors w/ SQUIDs
   - Ultra-high R silicon thermometers w/ CMOS
   - Kinetic Inductance thermometers w/ HEMTs
   - Hot Electron Bolometers w/ readout?
   - Cold Electron Bolometers w/ quasiparticle amplifier

Irwin

Zmudzinas

Matsuo

Yngvesson; Karpov

June 10, 2004

Beyond Spitzer & Herschel

DjB - 49
Design Considerations

Beam Formation

Focal Plane Utilization

Background, Sensitivity

Readout, Format

Simultaneous Spectral Coverage

Temporal Response, System 1/f Noise

Observing Strategy

System Implementation

Detector Design
Development Life Cycle

Good Ideas

Space Missions

Suborbital Instruments
Development Life Cycle

- Good Ideas
- Space Missions
- Suborbital Instruments
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Technology Development Issues
(paraphrasing John Mather)

- First: what is compelling science in 2004, and what will be compelling in 2010+?
  - Immune to competition from other facilities
  - Matches major NASA/ESA themes
- Second: where will technical capability be in 2010+?
  - Optical designs are (mostly) conceptually mature
  - Detectors evolving rapidly, but must continue
  - What can we make ready for space flight?
- Third: What can fit in mission payloads?
  - Mass
  - Volume
  - Power
  - Temperature
  - Cost
### SAFIR Instrument Complement

*From Harvey et al. (2002); Amato et al. (2002)*

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<td>Sensitivity $\sim$7 years Format $\sim$2 years</td>
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<td>Multiple Receivers</td>
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<td>Sensitivity $\sim$few years Format $\sim$few years</td>
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Take-Home Messages

• Big cold telescopes in space are coming, and have tremendous capability

• Imaging instruments have many options, so must be science-driven (large areas? polarimetry?)—as well as technology-driven:
  – Erick Young - large photoconductor arrays
  – Kent Irwin - large bolometer arrays

• Spectrometers in the far-IR are challenging
  – Matt Bradford - direct spectrometry
  – John Pearson - heterodyne spectrometry
  – Jonas Zmuidzinas - superconducting spectrometers

• Can you do the science = can you build the detectors