The SPICA Coronagraph

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Introduction on JAXA, ISAS, and AKARI

- **JAXA (Japan Aerospace Exploration Agency)**
  - The space agency of Japan.
- **ISAS (Institute of Space and Astronautical Science)**
  - A division of JAXA for space and astronautical science.
- **AKARI**
  - IR surveyor mission by ISAS/JAXA.
  - Cooed 68.5 cm telescope for 1.7–180 micron observation (~ SPITZER).
  - Launched in Feb. 2006 by a M–5 rocket of ISAS.
  - All sky survey is successfully undergoing.
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Now AKARI is working in orbit!
SPICA (Space Infrared telescope for Cosmology and Astrophysics)

- Observatory type IR telescope mission (⇔ AKARI is a surveyor)
- Orbit: halo orbit around Sun–Earth L2 point
- Launch: in the Middle of 2010s
- Rocket: H–IIA rocket of JAXA
- Telescope
  - Aperture: 3.5m
  - Core wavelength: 5–200 micron
  - Optics type: on–axis Ritchey–Chretien
  - Temperature: 4.5 K
  - Mirror: monolithic mirror of SiC or C/SiC

SPICA is the next generation IR telescope mission led by JAXA following to AKARI.
# SPICA instruments

<table>
<thead>
<tr>
<th></th>
<th>NIR instrument (optional)</th>
<th>MIR instrument</th>
<th>Coronagraph instrument</th>
<th>FIR instrument</th>
<th>Sub-millimeter instrument (optional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ ($\mu$m)</td>
<td>2 – 5</td>
<td>5 – 40</td>
<td>5 – 28</td>
<td>28 – 200</td>
<td>200 – 600</td>
</tr>
<tr>
<td>Detector</td>
<td>InSb</td>
<td>Si:As, Si:Sb</td>
<td>Si:As</td>
<td>Ge:Ga, bolometer</td>
<td>Bolometer</td>
</tr>
<tr>
<td>FoV</td>
<td>6.1’ × 6.1’</td>
<td>6.6’ × 6.6’</td>
<td>1’.0 × 1’.0</td>
<td>7.7’ × 7.7’</td>
<td>TBD</td>
</tr>
<tr>
<td>$\Delta \theta$</td>
<td>0”.35</td>
<td>0”.35 – 2”.8</td>
<td>0”.35 – 2”.0</td>
<td>2”.0 – 14”</td>
<td>14” – 42”</td>
</tr>
<tr>
<td>$\Delta \lambda / \lambda$</td>
<td>-</td>
<td>~3000</td>
<td>~200</td>
<td>~2000</td>
<td>~1000</td>
</tr>
<tr>
<td>note</td>
<td>Imaging mode only.</td>
<td></td>
<td></td>
<td></td>
<td>Contrast:10^{-6}</td>
</tr>
</tbody>
</table>

We are going to develop a MIR coronagraph as one of FPI of SPICA.
Target of the SPICA coronagraph

- Primary target
  - Contrast in MIR
    - 10^{-6} : realistic target for near future coronagraph
  - Self-luminous warm (1-5 Gyr old) planets (Tamura et al.2000)
  - Diffraction limit:
    - 10AU@10pc \rightarrow 3 \lambda / D (\lambda = 5 \mu m, D = 3.5m)
  ⇒ Jovian planets rather than Terrestrial planets

- Other target
  - Circumstellar environment of red giant
    (contrast: 10^{-4} - 10^{-5}@ \lambda = 20micron)
  - Proto–planetary disk around YSO, Debri disks
    (contrast: 10^{-3}@ \lambda = 5–20micron)

Primary target:
Systematic detection and spectroscopy survey of self–luminous warm Jovian exo–planets (around 1–5 Gyr old)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core wavelength ((\lambda))</td>
<td>5–27 micron (3.5–5 micron is optional)</td>
</tr>
<tr>
<td>Observation mode</td>
<td>Imaging, Spectroscopy</td>
</tr>
<tr>
<td>Coronagraphic mode</td>
<td>binary shaped pupil mask, Hybrid (binary shaped pupil + PIAA)</td>
</tr>
<tr>
<td>Inner working angle (IWA)</td>
<td>(\sim 3.5 \times \lambda / D) (binary shaped pupil mask mode) (\leq 2 \times \lambda / D) (hybrid mode) (\leq 10 \times \lambda / D) (hybrid mode)</td>
</tr>
<tr>
<td>Throughput</td>
<td>(\sim 30%) (binary shaped pupil mask mode) (\sim 80%) (hybrid mode)</td>
</tr>
<tr>
<td>Outer working angle (OWA)</td>
<td>(\sim 30 \times \lambda / D) (binary shaped pupil mask mode) (\sim 10 \times \lambda / D) (hybrid mode)</td>
</tr>
<tr>
<td>Contrast</td>
<td>Higher (better) than (10^{-6})</td>
</tr>
<tr>
<td>Detector</td>
<td>1k \times 1k format Si:As array, 0.”1/pixel</td>
</tr>
<tr>
<td>Field of View</td>
<td>20WA \times 20WA</td>
</tr>
<tr>
<td>Bandpass filter</td>
<td>3.5–4.5, 4.5–5.5, 5.5–8, 8–12, 12–18, 18–27(micron)</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>(&lt;) IWA</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>(~ 200)</td>
</tr>
<tr>
<td>Spectroscopy method</td>
<td>Slit + bandpass filter + disperser</td>
</tr>
<tr>
<td>Slit width</td>
<td>0.2”, 0.4”, 0.8”, 1.6”, 3.2”</td>
</tr>
<tr>
<td>Slit scan</td>
<td>2D slit scanning on a focal plane is available</td>
</tr>
<tr>
<td>Heat generation</td>
<td>(&lt;) a few mW</td>
</tr>
<tr>
<td>Data rate</td>
<td>0.62 Mbps</td>
</tr>
</tbody>
</table>

Spec. of contrast: \(hither than 10^{-6}\)
Coronagraph selection for SPICA

- **SPICA coronagraph**
  - use in MIR, Obscuration in pupil, Satellite vibration.. 
  - Contrast is 10-6 but it’s still challenging. 
  - We have to develop the flight model in our schedule.

The 1\textsuperscript{st} priority: to get a feasible and robust solution
  → Shaped pupil mask coronagraph 
    (Princeton team pioneered. see presentation of Belikov et al)

The 2\textsuperscript{nd} priority: to improve performance
  → PIAA/binary mask hybrid 
    (e.g., Guyon2003. see presentation of Abe et al., Guyon et al., poster of Tanaka et al, Totem et al.)
Experiment: Mask design

**Mask1**       **Mask2**

- Checkerboard mask (Vanderbei, Kasdin, Spergel 2004)
- LOQO optimizer (Vanderbei 1999) used
- Study for optimization for obscured pupil (Tanaka, Enya, Abe, Nakagawa, Kataza 2006; Enya, Tanaka, Abe, Nakagawa 2006)

<table>
<thead>
<tr>
<th></th>
<th>Mask 1</th>
<th>Mask 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Symmetric</td>
<td>Symmetric</td>
</tr>
<tr>
<td>Central obstruction</td>
<td>30%</td>
<td>No obstruction</td>
</tr>
<tr>
<td>IWA <em>(λ/D)</em></td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>OWA <em>(λ/D)</em></td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td><strong>Contrast</strong></td>
<td>10^-7</td>
<td>10^-7</td>
</tr>
<tr>
<td>Throughput <strong>(%)</strong></td>
<td>16</td>
<td>24</td>
</tr>
</tbody>
</table>

- Checkerboard Mask1, Mask 2 were optimized
  - Required contrast: 10^-7
  - Beam diameter: 2mm

Checkerboard mask: fabrication

- KB7 substrate: 30mm diameter, 2mm thickness
- Al film: 100nm thickness
- Electron beam patterning in collaboration with AIST (National Institute of Advanced Industrial Science and Technology)
- Lift off process
- AR coating for both sides

Precise fabrication method was developed with AIST using electron beam patterning
Experiment configuration

- Clean and dark room, air suspension optical bench
- For high dynamic range measurement:
  - ND filter (OD=2–4)
  - Various exposure time (0.03–10 sec)
- CCD temperature: 0 °C
- Dark frame was subtracted
Result: image of PSF

- **PSF core**
  - Quite consistent with design

- **Dark region**
  - Scatter in the camera is a serious problem
  - Measured with core blocking mask
  - Speckle limited pattern
  - Limit of design

Contrast: \(2.7 \times 10^{-7}\) (mask1), \(1.1 \times 10^{-7}\) (mask2)
Result: image of PSF

Core    Dark region

- PSF core
  - Quite consistent with design
- Dark region
  - Scatter in the camera is a serious problem
    - Measured with core blocking mask
  - Speckle limited pattern
  - Limit of design

Designed PSF

Mask1    Mask2

Contrast: 2.7x10^{-7} (mask1), 1.1x10^{-7} (mask2)

Higher contrast than SPICA’s requirement (10^{-6}) is demonstrated!
PIAA/Binary mask hybrid Coronagraph (see poster of Tanaka et al., Totem et al.,)

- PIAA (Guyion 2003)
  - small IWA
  - high throughput
  - reflective optics
  - manufacture of mirror is very challenging

- PIAA/Binary mask hybrid solution
  - relax difficulty of mirror manufactureing

IWA $\sim 1.5 \lambda / D$

Contrast $6.5 \times 10^{-7}$
PIAA/Binary mask hybrid Coronagraph (see poster of Tanaka et al.)

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  - small IWA
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  - reflective optics
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Higher contrast than SPICA’s requirement ($10^{-6}$) is demonstrated!

IWA $\sim 1.5 \frac{\lambda}{D}$
Contrast $6.5 \times 10^{-7}$
Summary

- SPICA is the next generation IR telescope mission led by JAXA following to AKARI.

- We are developing the MIR–coronagraph for SPICA.

- The primary target of the SPICA coronagraph is self-luminous Jovian exo-planets.

- We demonstrated SPICA’s requirement contrast ($10^{-6}$) was satisfied with visible light.
  - Shaped pupil mask coronagraph ($1.1 \times 10^{-7}$) ⋯ as the feasible, robust solution
  - PIAA/Binary hybrid ($6.5 \times 10^{-7}$) ⋯ as the high performance mode

- Next step:
  - demonstration with visible light → MIR coronagraph demonstration
  - higher contrast???