The JASMINE mission
(Japan Astrometry Satellite Mission for INfrared Exploration)

Daisuke Kawata (JASMINE Project Scientist, Mullard Space Science Laboratory, University College London)
Hajime Kawahara (JASMINE Exoplanet Science lead, ISAS/JAXA)
Naoteru Gouda (JASMINE Principal Investigator, NAOJ)
and
JASMINE team
In Japan, NIR astrometry mission planning started around 2000.

**Challenge:** NIR detector cannot scan the sky unlike CCD used by Gaia

---

**Hop:** Nano-JASMINE   **launch date:** July 2010
- very small nano-satellite: 25kg, 50³cm³
- the diameter of a primary mirror: 5cm
- the first space astrometry in Japan

**Step:** Small-JASMINE  **target launch date:** ~2015
- step-by-step approach to JASMINE for both science and techniques
- the diameter of a primary mirror: 30cm
- weight of a satellite: ~400kg
- survey toward the restricted regions of the Galactic bulge

**Jump:** JASMINE     **target launch date:** the first half of 2020’s
- the diameter of a primary mirror: 80cm
- weight of a satellite: ~1500kg
- survey toward the whole region of the Galactic bulge

---

*Gouda et al. (2009)*
JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration) selected for JAXA Science Mission M-Class #3 (planned launch in 2028) NIR astrometry and time-series NIR photometry

M-mission with Epsilon launcher every 2 years

36 cm diameter, limiting magnitude: $H_w(1.0-1.6 \mu m)=9-14.5$ mag

$H_w \sim 0.941J+0.059H-0.045(J-H)^2$
<table>
<thead>
<tr>
<th>年度</th>
<th>令和2年度 (2020年度)</th>
<th>令和3年度 (2021年度)</th>
<th>令和4年度 (2022年度)</th>
<th>令和5年度 (2023年度)</th>
<th>令和6年度 (2024年度)</th>
<th>令和7年度 (2025年度)</th>
<th>令和8年度 (2026年度)</th>
<th>令和9年度 (2027年度)</th>
<th>令和10年度 (2028年度)</th>
<th>令和11年度 (2029年度)</th>
<th>令和12年度以降</th>
</tr>
</thead>
<tbody>
<tr>
<td>はやぶさ2の運用</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>地球帰還</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>拡張ミッションの機器</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>新たな小惑星の探索等の拡張ミッションの実施</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X線分光撮像衛星 (XRISM) の開発</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>運用</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>水星磁気圏探査機「みお」 (MMO) の運用</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>戦略的に実施する中型計画に基づく衛星 (10年で3機)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>火星衛星探査計画 (MMX) 開発</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiteBIRD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>運用</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>公募型小型計画に基づく衛星 (2年に1回)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>小型月着陸実証機 (SLIM) の開発</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>運用</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>深宇宙探査技術実証機 (DESTINY+) の開発</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>運用</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>小型JASMINE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar-C (EUVST)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Japanese Consortium and International collaboration
JASMINE two main science goal

• Galactic Centre Archaeology
  - To reveal the Milky Way’s central core structure and its formation history
  - To explore the formation history of the Milky Way structures, like the bar, which triggered the radial migration of the Sun

\[\iffalse\]
NIR astrometry of the Galactic centre
\[\iffalse\]
Unexplored territory of the ESA Gaia mission, but NIR MOS (MOONS, SDSS-V, Subaru/PFS) will provide spec data in late 2020s!

• Exoplanets
  - To discover Earth-like habitable exoplanets

\[\iffalse\]
NIR time-series photometry of M-dwarfs
\[\iffalse\]
Target for JWST, ARIEL spec follow-up!
Galactic Centre Survey (Rgc~200 pc)
Near-IR : see through the dust in the disk

Optical: Gaia
NIR: Nishiyama et al.
Galactic Centre Survey (Rgc~200 pc)

- Main astrometry survey (spring, fall)
- Precise NIR astrometry, with ~100K obs. in 3 years.

**Hw<12.5 (14.5) mag, 25 (125) μas**

(Verr < 5 km/s, N~10^5) ⇒ Galactic centre structure

- 12.5s exp. x 20 every ~100 min cadence photometry (TBD)
- Serendipitous sciences
  - (IM)BHs, microlensing, binary
  - Ultra light DM, soliton core
  - High velocity stars
  - X-ray and radio sources.
  - Solar system objects

Nishiyama et al.
Galactic Centre Archaeology: Galactic Nucleus

Nuclear Stellar Disk (NSD \( \sim 10^9 \) M\(_\odot\))
Main JASMINE target!
N \~\sim 10K with JASMINE

Nuclear Star Cluster (NSC\( \sim 10^9 \) M\(_\odot\))
\~100 stars with JASMINE

Gallego-Cano et al. 2020
NSD will tell us the epoch of the Galactic bar formation

Hierarchical clustering at the early Universe

The burst of star formation in the cold nuclear disk (NSD) = the formation epoch of the Galactic bar
Bar formation epoch ~ formation epoch of NSD
Impact to radial migration of the Sun?
Bar (strong impact on the orbits of stars) or the Sun, which one formed earlier? key to study the past orbit of the Sun.

Our way through the Milky Way

The solar system is travelling at a steady 220 kilometres per second in a circular orbit around the centre of the galaxy - but it might not always have done so

- Passing through dark interstellar dust could have altered Earth's climate - perhaps leading to episodes of global glaciation.
- The Sun and planets may have originated closer to the galaxy's centre and "surfed" outwards along its spiral arms.
- As the entire galaxy moves through the cosmos, its bow shock sends a deluge of cosmic rays raining down.
- The solar system wobbles up and down 200 light years either side of the galaxy's disc. When it wobbles above, Earth may be exposed to more cosmic waves from the galaxy's bow shock.
- Passing through bright star-forming regions might have exposed Earth to hazardous radiation from supernovae - perhaps causing mass extinctions.
Age tracers: e.g. Mira variables

Proper motion from JASMINE will help to select NSD Miras (Baba & Kawata 2020).

Identifying Galactic Centre Miras with PRIME (NIR bulge microlensing survey telescope 2022- led by Osaka U.)

Grady et al. (2019)
Missing Intermediate mass ($100-10^5 \, M_\odot$) Black Hole (IMBH)!

Stellar mass BH($\leq 100 \, M_\odot$)

Super-massive BH (e.g. Galactic SMBH, $4\times10^6 \, M_\odot$)

~20 years of motion of stars around the SMBH (2020 Nobel Prize)

Gravitational Wave detection of BHs (2017 Nobel Prize)

ESO/M. Parsa/L. Calçada
Hunting (IM) Black Holes in the Galactic centre?

- e.g. Runaway merger IMBH near SMBH (e.g. Portegies Zwart et al. 2006)
- Remnants of dwarf galaxy mergers

30 non-interacting BH-star binary expected from JASMINE Galactic Centre Survey (Yamaguchi et al. 2018).

About 10 microlensing event expected. Photometric + Astrometric microlensing $1000 \ M_\odot\ BH@d=7.5 \ kpc, \sim700 \ days\ \Theta_E\sim8.2\ mas$ (Toki & Takada 2022)

**Synergy with SUBARU ULTIMATE** (NIR wide-field AO, faint stars populations and motion with JASMINE reference frame)
Spring and Autumn: NIR Astrometry Galactic Centre Survey (GCS)
Summer and Winter: Exoplanet survey (EPS): M-dwarf transit

EPS potential target M-dwarf

Observable days in summer and winter

Exoplanet Science Team: Kawahara, Masuda, Fukui, Hirano, Kotani, Kodama, Kuzuhara, Omiya, Takahashi, Kasagi, Kawashima, Tada, Miyakawa
M-type cool stars are brighter in NIR
High-precision photometry exploration of Habitable Zone (HZ) Earth-like planets

- Star: 3000K, 0.2 R\(_\odot\), 0.2 M\(_\odot\)
- Earth-like planet: Earth-size transit depth = 0.2-0.3%
- HZ orbits: ~ 2 weeks

JASMINE Transit Simulation (Hirano et al.)

Relative Flux vs. Time (min)
Niche capability of JASMINE Exoplanet survey

**Stellar mass (log)**
- $1M_\odot$
- $0.1M_\odot$

**Distance from a star (log)**
- 0.01 AU
- 0.1 AU
- 1 AU

**Distance from a star (log)**
- **Ground-based telescope**
- **Habitable Zone**
- **Follow up by JASMINE as done by Spitzer**

**HZ transit detection rate for the system found with inner planet transit** = 20-40%

2~5 HZ Earth-like planets from 25 observations

**TESS**
- $D=10cm$
- 0.6-1.1um

**Trappist-1**
- $D=36cm$
- 1.0-1.6 μm

**TOI-700**

**Roman/CGI**

**JASMINE**

**Spitzer**

**NASA flagship**

**地上 + Spitzer**

**HZ transit detection rate for the system found with inner planet transit** = 20-40%

2~5 HZ Earth-like planets from 25 observations
Other potential targets for exoplanet survey I: Young star clusters

- Exoplanets around ~1,000 cool young stars?
- Taking an advantage of FoV 0.55 x 0.55 deg$^2$, small pixel size of 0.47 arcsec
Other potential targets II: Astrometric Planet Survey

- Ultra cool dwarfs (too red for Gaia): Is there any giant planets?
- Known RV lor DI long-P system, combined with Gaia, ~20 years baseline
- Astrometric microlensing for nearby (<500 pc, very rare) microlensing sources

3 years of Galactic centre survey: astrometric and transit

![Astrometry Diagram](https://example.com/astrometry_diagram.png)
Thermal stability is crucial
Super-Super Invar alloy (coefficient of thermal expansion) $0 \pm 5 \times 10^{-8}$ /K
Mirrors of CLEARCERAM®-Z EX (CTE: $0 \pm 1 \times 10^{-8}$ /K)
Telescope temperature control within $278 \pm 0.1$ K for 50 min.

2x2 New InGaAs NIR detector (1920x1920 pix, NAOJ)

Flat calibration for inter- and intra-pixel uniformity is crucial.
Flat light source on board (Kotani et al.)
Galactic Centre programme: Nobs ~ 20 images x 8,000 orbits

Astrometric accuracy improved by $\sqrt{\text{Nobs}}$, i.e. ~1/400

---

~4mas @ Hw=12.5 mag

~1 mas @ Hw=12.5 mag

~25 μas @ Hw=12.5 mag

---

**Step A**

Obtain stellar images and measure the centroids of the stars.

**Step B**  (Use Gaia reference)

Stitch the distorted frames and estimate the positions on a large frame.

**Step C**

Estimate astrometric parameters from thousands of measurements.

Credit: R. Ohsawa
In more realistic mock data

Expected on-sky motion of a star

Possible measurements

$\omega = 0.3 \text{ mas, } \mu = 0.3 \text{ mas/yr, } \sigma = 1 \text{ mas}$

Credit: R. Ohsawa
Astrometric and photometric accuracy with many images end-2-end simulation Team:
Ohsawa, Kamizuka, Kawahara, Hirano, Aizawa, Miyakawa, Yamada, Kataza et al.
ARI-Heidelberg: Michael Bierman, Wolfgang Lößler et al.

JASMINE Image Simulator (JIS)

- Wave Front Error (PSF, optical distortion chromatic aberration)
- Detector (inter/intra pixel sensitivity, pixel distortion, noise)
- Attitude Control Error, Aberration

JASMINE Astrometry Data Analysis (JADA)

- Background subtraction
- Star image extraction
- Build ePSF
- Centroid estimates
  ~4 mas @Hw~12.5

Distortion correction, using stars in the overlapped frames. **Thermal stability!**
~1 mas

3yrs data
8,000 frames
1 orbit

Distortion correction, using stars in the overlapped frames. **Thermal stability!**
~1 mas

Astrometry Parameter
\((\alpha,\delta,\pi,\mu_\alpha,\mu_\delta)\)
~25 \(\mu\)as @Hw~12.5 mag

in point source catalogue \((\alpha,\delta,\pi,\mu_\alpha,\mu_\delta)\),
From catalogue, (2MASS, Sirius, VVV), incl. background stars + binary, variables, microlensing…

Thermal stability!
~1 mas
Synergy with the other missions and projects

Astrometry/Galactic archaeology

Gaia: 2013-25(?)

Gaia Final Full Data Release: >2028(?)

PRIME+SAND 2022-

ULTIMATE-Subaru 2027-

Subaru/PFS: 2023-

SDSS-V Milky Way Mapper: 2020-25

VLT/MOONS: 2022(?)-, WEAVE, 4MOST

JASMINE (2028-2031)

JWST: 2021-2031(?)

Roman: 2026-203?

ARIEL: 2029-2032(?)

GaiaNIR: 2045(?)-

Exo-Planets
Summary

- JASMINE will be the first NIR space astrometry mission with planned launch in 2028, a pioneer for GaiaNIR.
- Two goals of Galactic centre archaeology and exoplanet science.
- As seen in Gaia, the astrometry mission provides the new dimension of data: the JASMINE data will be valuable for wide-range of sciences, including targeted and serendipitous targeted discovery of diverse exoplanet populations.
- You are welcome to join!
Galactic Centre programme: Nobs ~ 20 images x 8,000 orbits
Astrometric accuracy improved by $\sqrt{\text{Nobs}}$, i.e. $\sim 1/400$

One orbit ~ 100 min, and GC is observable ~50 min.

Sun Synchronous orbit with LTAN 6:00 or 18:00

Overlap of small fields to correct the optical distortion

12.5 sec exposure

0.55 x 0.55 deg$^2$

Small Frame

Old version of GC field!

Large Frame

Detail strategy will be adjusted for the new detector…

(TBD)

Combined data of 16 small frames = large frame

Avoid earth oriented attitude

20 images 12.5 sec/image Small Frame
Magnitude of 250th brightest star in the sample of $dR = 0.1 \, R_\odot$ bin

Transit depth of Earth-size planet
現在の時点でのターゲット。
加えて、褐矮星変動、若い惑星探査など赤外精密測光を活かした独自性の高い探査も検討中。

加えて、褐色矮星変動、若い惑星探査など赤外精密測光を活かした独自性の高い探査も検討中。