Small-JASMINE

JASMINE working group

Ver 20171205
# 1. Scientific goals and objectives

**Review viewpoint**

## (A) To assess Scientific significance of small JASMINE in astronomy and astrophysics

<table>
<thead>
<tr>
<th>Scientific goal</th>
<th>Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Is the main science goal of the mission, elucidating formation process of supermassive black hole by studying the phase-space distribution of the stars in the bulge, fully justified?</td>
<td>Chapter 2.1 p.23, p.24, Appendix pp.3<del>27 Presentation=&gt;p.16</del>p.22</td>
</tr>
<tr>
<td>(2) Small JASMINE obtains the astrometric information with very high precision, 20 micro arcsec in parallax, for more than a few thousand stars in the bulge. How the data set can be extensively utilized for more general study of the Galactic bulge?</td>
<td>Chapter 2.1, 2.2, 2.4 Presentation=&gt;p.12<del>p.14, p.23</del>p.38 p.45</td>
</tr>
<tr>
<td>(3) On the assumption that NASA WFIRST, a future mission extensively observing the Galactic bulge, will be implemented in 2025 as planned, can the small JASMINE be compelling in science if it is launched in mid-2020?</td>
<td>Chapter 2.5 (pp.53<del>60) Presentation=&gt;p.50</del>p.54</td>
</tr>
</tbody>
</table>

## (B) To assess the technical feasibility of Small JASMINE to obtain the required accuracy in astrometry

<table>
<thead>
<tr>
<th>Technical feasibility query</th>
<th>Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Are the error budget plan and the expected uncertainty in evaluation of the errors valid?</td>
<td>Chapter 4: Description of background pp.114, 115: Table of error budget Chapter 5: basis of allocation</td>
</tr>
<tr>
<td>(2) Are the development policy, verification policy, and verification method valid?</td>
<td>Chapter 6 Summary p.194</td>
</tr>
</tbody>
</table>
1.1 Mission Overview/Astrometry

Astrometry: Fundamental task of measuring stellar positions

Repeated measurements (2D-positions of stars in space)

Trajectory of a (single) star: Helical motion

Annual parallactic ellipse + proper motion (straight line)

distance

tangential velocity

*Residual motions from the helical motion

Very important information!!

Binary systems, Planetary systems, Gravitational micro-lens effects, effects of starspots, etc.

Necessity of high precision measurements \(\leq\) stars are very far and so the annual parallaxes and the proper motions are very tiny

Space astrometry mission

★Great success of Hipparcos!! (0.3~1 mas, \(\sim\)120,000 stars)

Big revolution!!

★Gaia (0.5~500\(\mu\)as, \(\sim\)1,000,000,000 stars)
1.2 Mission Overview / Outline of SJ

Small-JASMINE (SJ)

SJ will make a catalogue which includes the time-series data of the stellar positions on the celestial sphere, parallaxes, proper motions and some physical characters derived by the time-series data and will release this catalogue to public across the world.

The characteristics of the Small-JASMINE mission are given as follows.
1.2 Mission Overview / Outline of SJ

Outline of Small-JASMINE

Astrometric Measurement in Hw-band
(1.1\textmu m\sim 1.7\textmu m)

Infrared astrometry missions have advantage in surveying the Galactic nuclear bulge, hidden by interstellar dust in optical bands!

Two survey modes

1. survey for the key project in spring and autumn

   Nuclear bulge around the Galactic centre

2. survey for open use in summer and winter

   some directions towards interesting target objects

   Advantage of Small-JASMINE: every 100 minutes!

   Highly frequent measurements of the same target

   Phenomena with short periods

(e.g. Cyg X-1, planetary systems of brown dwarfs, star-forming regions outside the area around the centre)
1.2 Mission Overview / Outline of SJ / Understanding of the Galaxy

1.2.1 Mission Overview / Outline of SJ / Key Project

★ The details of the survey mode for the key project
(towards the Galactic nuclear bulge)

Survey region 1:
circle with the radius of 0.7 degree (~100pc) around the Galactic centre

• number of observable stars
  bulge stars: ~4900 (Hw<12.5mag)
  (disk stars:~3500 (Hw<12.5mag) common with stars measured by Gaia)

This survey region makes it possible to determine whether or not relatively small supermassive black holes fall into the Galactic centre and results in the change of the density profile and velocity dispersion profile of stars in the Galactic nuclear bulge. Please refer to the scientific objective A-1-(i).

Survey region 2:
Survey region: Galactic longitude -2.0 ~ 0.5 degree
  Galactic latitude 0.2 ~ 0.5 degree

• number of observable stars
  bulge stars: ~5000 (Hw<12.5mag)
  (disk stars:~1600 (Hw<12.5mag))

This survey region makes it possible to determine whether an inner bar exist. Please refer to the scientific objective A-1-(ii)
Astrometric Precisions in the key survey-mode:
parallax and position:
$< \sim 20\mu\text{as for } \text{Hw}<12.5\text{mag}$
proper motion:
$< \sim 20\mu\text{as/yr for } \text{Hw}<12.5\text{mag}$
(photometry (Hw-band): $<0.01\text{ mag}$)

The main purpose of Small-JASMINE

Small-JASMINE will provide a catalogue for parallaxes, proper motions with the above precisions and time sequences of stellar positions on the celestial sphere in the survey region of the key project.
1.2.2 Mission Overview / Outline of SJ / Open Use

★Survey mode for open use in summer and winter seasons

We will accept mission proposals from an open call to the scientific community. A time-allocation committee will select targets and their priority.

Examples of candidates for scientific targets:
- X-ray binaries (e.g. CygX-1), γ-ray binaries, planetary systems of brown dwarfs, star-forming regions outside the area around the Galactic centre, etc.

*the individual astrometric precision of these open-call target-objects depends on each target itself while the overall precisions are restricted by the designed system of the satellite.*
Complement of the Gaia mission in Small-JASMINE

* Gaia can measure the parallax of only about 80 bulge stars with high precisions (<20μas) within the Small-JASMINE survey region around the Galactic centre due to the effect of absorption by the interstellar dust.

SJ (Small-JASMINE) => ~8900 bulge stars

* Gaia can measure the same target every ~50 days(#).

So Gaia cannot resolve the astrophysical phenomena with much shorter periods than around 50 days.

#On average, each object on the sky is observed about 70 times (two astrometric fields combined and 20% total dead time assumed)

https://www.cosmos.esa.int/web/gaia/scanning-law

⇒ the same target can be measured every ~50 days

SJ=> every 100 minutes

*IAU Commission A1 (astrometry) recommends Small-JASMINE for its unique infrared space astrometry mission!
2.1 Science Goals and Mission Requirements

Science Goal

Clarify galaxy formation and evolution through research of the Milky Way Galaxy as a testing ground

The Milky Way: very important target galaxy!!

It is possible to observe in the Milky Way individual stars to obtain information on their 3-dimensional positions, 3-dimensional velocities (and metallicity) with good accuracies, which is, in general, still not possible for galaxies outside the Milky Way.

Small-JASMINE have a lot of concrete scientific objectives to achieve the above goal.

★Examples of scientific objectives of Small-JASMINE are shown in the succeeding slides
2.1 Science Goals and Mission Requirements / Scientific Objectives

A. **Astrophysics in the Galactic nuclear bulge around the Galactic centre: key project (in spring and autumn)**

A-1: Characterise the dynamical structures of the Galactic nuclear bulge to clarify energy sources fed into the Galactic centre and investigate the evolution of the Galactic nuclear bulge

A-2: Clarify formations of stars and star clusters around the Galactic nuclear bulge

A-3: Investigate compact objects around the Galactic nuclear bulge

A-4: Understand stellar physics and interstellar medium

B. **Astrophysics in different directions to the direction of the Galactic nuclear bulge in open-use program (in summer and winter)**

Galaxy formation and evolution

Galaxy evolution
## 2.1 Science Goals and Mission Requirements / Scientific Objectives

### Science traceability matrix

<table>
<thead>
<tr>
<th>Science goal(s)</th>
<th>Science objectives</th>
<th>Investigations</th>
<th>Observables</th>
<th>Instruments</th>
<th>Requirements</th>
<th>Mission data requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clarify galaxy formation and evolution through research of the Milky Way</td>
<td>1. Characterize the dynamical structures of the Galactic nuclear bulge to clarify</td>
<td>Density profile of bulge stars (&lt;100pc from the Galactic centre).</td>
<td>Stellar trajectories on the celestial sphere and the following astrometric parameters derived by the stellar trajectories.</td>
<td>Aperture size of the optical telescope</td>
<td>30 cm</td>
<td>Survey region: (1) the circle with a radius of 0.7 degree around the Galactic centre (2) Galactic longitude 2°-0.5 degree Galactic latitude 0.2°-0.5 degree Parallax error: &lt;=20μas Proper motion error: &lt;=20μas/yr Number of observable bulge stars within the survey region(1) : &gt;=3500 Number of observable bulge stars within the survey region(2) : &gt;=2000</td>
</tr>
<tr>
<td>Galaxy as a testing ground</td>
<td>energy sources fed into the Galactic centre and investigate the evolution of the</td>
<td>Multiphase space distributions of bulge stars (&lt;100pc from the Galactic centre).</td>
<td>*Annual parallaxes *Proper motions *Positions on the celestial sphere at a certain time</td>
<td>Wavelengths for the observation</td>
<td>1.1mm-1.7mm</td>
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<td></td>
<td>Galactic nuclear bulge</td>
<td></td>
<td></td>
<td>Image accuracy on focal plane after calibration</td>
<td>&lt; 0.1nm (5.7μas)/50 min</td>
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<td></td>
<td>Image stability on focal plane</td>
<td>&lt;10nm/50min</td>
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<td>Thermal stability of support struts</td>
<td>&lt;=50nm/50min</td>
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<td>Thermal stability of mirror surface</td>
<td>&lt;=0.6nm (off plane), 4nm (in plane) /50min (in plane)</td>
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<td></td>
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<td>Thermal stability of detector</td>
<td>&lt;=0.5nm (off plane), 2nm (in plane) /50min (in plane)</td>
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<td></td>
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<td>Focal length change</td>
<td>&lt;=10nm /50min</td>
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<td></td>
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<td>Alignment drift by thermal distortion</td>
<td>&lt;= 27mas / 7.1sec</td>
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<td></td>
<td></td>
<td>Detector temperature</td>
<td>&lt;=180K</td>
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<tr>
<td></td>
<td>2.Clarify formations of stars and star clusters around the Galactic nuclear bulge</td>
<td>Motions of stars in star clusters</td>
<td></td>
<td>Parallax error: &lt;=25μas</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Motions of stars around the Galactic nuclear bulge</td>
<td></td>
<td>Proper motion error: &lt;=20μas/yr</td>
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<td></td>
</tr>
</tbody>
</table>
### 2.1 Science Goals and Mission Requirements / Scientific Objectives

<table>
<thead>
<tr>
<th>Science goal(s)</th>
<th>Science objectives</th>
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<th>Mission data requirements</th>
</tr>
</thead>
</table>
| 3. Investigate compact objects around the Galactic nuclear bulge | Orbital elements of binary systems  
Astrometric gravitational microlens effects (stellar trajectory on the celestial sphere) | Stellar trajectories on the celestial sphere (deviation from the helical motion annual elliptic motion + proper motion (straight line)) | Design parameters | Error of the measurement of the deviation is less than ~20μas which corresponds to the requirement of the parallax of ~20μas |
| 4. Understand stellar physics and interstellar medium | Distances of stars | Annual parallaxes | | | | Parallax error: <= 25μas |
| Second objectives in the survey mode for open use program:  
Examples | | | | | | Scientific operation in summer and winter seasons toward directions of target objectives selected among proposals for open use |
| Clarify X-ray binaries and γ-ray binaries | Orbital elements of binary systems | | | | |
| Investigate exoplanets of bright primary stars in an infrared band | Orbital elements of planetary systems  
Astrometric gravitational microlens effect (stellar trajectory on the celestial sphere) | | | |
| Clarify stellar hot spots | Motion of a stellar photosphere | | | |
| Clarify physical characters of bright stars (<3.5 mag) in binary systems | Orbital elements of binary systems | | | |
2.1 Science Goals and Mission Requirements / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge

Scientific Objectives

A. Astrophysics in the Galactic nuclear bulge around the Galactic centre
Scientific objective A-1

Characterise the dynamical structures of the Galactic nuclear bulge to clarify energy sources fed into the Galactic centre and investigate the evolution of the Galactic nuclear bulge

*The nuclei of galaxies such as that of the Milky Way (the Galactic nuclear bulge) are extreme regions that typically host a supermassive black hole and extremely high stellar densities. Studies on these regions are very important and necessary to clarify evolutions and activities of the galaxies. However how galactic nuclei like the Milky Way’s formed remains an open question.

The only galactic nucleus where detailed stellar population properties can be derived with sufficiently high resolution and precision is that of the Milky Way, making it a fundamental testbed for different models for formations, evolutions and energy sources fed into the Galactic centre.
Verify the hypothesis that some supermassive black holes fall into the Galactic centre by the dynamical friction to form Sgr A*

1. If some supermassive BHs (> 100,000 solar mass: it is assumed that the total mass of the supermassive BHs is 4 million solar mass which corresponds to that of SgrA*) exist and they have fallen into the Galactic centre (<100pc) by the dynamical friction,

- the effect of the dynamical friction (and the release of the gravitational energy of BH binaries) “heat up” the stars around the centre area (<100pc).
- change of the density profile and the distribution of the velocity dispersion

*The stars within the radius of 100pc around the centre will be heated up

Change of the density profile and velocity dispersion profile of bulge stars within the radius of 100pc
2.1 Science Goals and Mission Requirements / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / SMBH

**Heated up profiles**

(Merritt et al. 2004, Tanikawa and Umemura 2014)

*density profile*  
absolute value of the power index:  
< ~0.5 (~10pc<r<~100pc)

**Profiles of bulge stars without “heating”**

*density profile*  
absolute value of the power index:  
>~1.0 (~10pc<r<~100pc)(Alexander 2005, http://adsabs.harvard.edu/abs/2005PhR...419...65A)

Please refer in more detail to appendix A.1.1 with respect to the profiles heated up due to the dynamical friction

Success criterion: determine with more than 99.7% confidence level whether or not both the density and the velocity dispersion profiles of bulge stars within 100pc from the Galactic centre correspond to the profiles heated up by the effect of dynamical friction due to the infall of some supermassive black holes.

* We assume here that the absolute power index of the density profile heated up is 0.5 and that of the density profile of bulge stars without heating is 1.0 because this case provides most severe mission requirement for errors of annual parallaxes etc. to discriminate the heated up profiles from the profiles without heating with the above confidence level.
2.1 Science Goals and Mission Requirements / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / SMBH

★ scaling law

The following are examples of time scales for the profiles of density and velocity dispersion of bulge stars to achieve the heated up profiles within around 100pc due to the sufficient dynamical frictions and the release of the binding energy.

★ cases for sufficiently effect of the dynamical frictions and the release of the binding energy (heated up profile within around 100pc)

Ex.1: 5 BHs with 0.8 million solar mass \(\rightarrow\) 1.5 billion years
Ex.2: 10 BHs with 0.4 million solar mass \(\rightarrow\) 3 billion years
Ex.3: 20 BHs with 0.2 million solar mass \(\rightarrow\) 6 billion years
Ex.4: 30 BHs with 0.13 million solar mass \(\rightarrow\) 9.5 billion years
Ex.5: 40 BHs with 0.05 million solar mass + 8 BHs with 0.25 million solar mass \(\rightarrow\) 9.5 billion years

most BHs would have merged until the present time.

Clump: Star cluster and/or gas cloud object with a mass smaller than a dwarf galaxy.
Can the Small-JASMINE observations discriminate between different models?

Tests were carried out by comparing mock catalogues derived from “observing” two simulations with different phase-space densities \( f(r, \sigma) \): (1) a model including the effects of dynamical friction resulting in the heated up profiles, (2) a model excluding the effects of dynamical friction. The models are based on the numerical results of Tanikawa & Umemura (2014) and show only small differences in their density profiles.

creation of mock catalogue

- parallax error: 10~80\(\mu\)as
- proper motion error: 50~3200\(\mu\)as/year
- radial velocity error: 2km/s
- the number of observable stars: 2000~5000
- survey region: the circle with the radius of 0.7 degree around the Galactic centre

trial models

- model1: true solution (for the case of sufficiently effect of the dynamical friction)
- model2: case for no-effect of the dynamical friction: use of the numerical results by Tanikawa & Umemura (2014) (severe case in which the difference of the density profiles between two models is little)

reliability: estimated by the use of Kullback-Leibler(DKL) divergence (See § A.1.1)

If \( X = \text{DKL(observations and model 2)} - \text{DKL(observations and model 1)} > 0 \) \( \Rightarrow \) correct!

Evaluate the number of times for \( X > 0 \) by the use of many samples
Results of the confidence level tests

- the number of observable stars: more than 3500
  → more than 99.7%

- Parallax error: less than 20μas
  → more than 99.7%

- Proper motion error: 200μas/year
  → more than 99.7%

Mission requirement: reliability: more than 99.7%
*The result shown in this scientific objective item means that Small-JASMINE can discriminate between different shapes of phase-space densities (such as mass density profiles, velocity dispersion profile etc.) with high confidence levels. We like to stress here that this result is independent of physical reasons which provide the shapes of phase-space densities. So even if the reasons for the shape of the profiles are different from the reasons shown before, there is no doubt that Small-JASMINE can discriminate between different shapes of the profiles and determine which model (or physical reason) is preferable with high confidence levels.

In this scientific objective, the discrimination between the density profile with cusp shape (the absolute value of the power index: $\gamma>1$) and one with core shape ($\gamma<0.5$) is dealt with as an example. But we can deal with any other shapes of phase space densities according to researchers' interest and/or models which researchers like to verify. The method for verification of the shapes of phase space densities, as shown in this scientific objective, is applicable to any other models with high confidence levels if the difference between phase space densities is not so tiny.
2.1 Science Goals and Mission Requirements / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / Figure Rotation

Scientific objective A-1-(ii)

Clarify the gravitational potential field in the Galactic nuclear bulge, in particular, the velocity of the figure rotation of the potential.

*Gas fueling is very important for the growth of SMBHs, activities of galactic nuclei, nuclear star bursts and the formation of super star clusters in the galactic central regions.

*need to clarify transport mechanism of gas to galactic centres

rotating bar=>Losing angular momentum and energy of gas
◎ candidate of key processes for transportation of gas:
◎ Nested bars:
  outer bar(~5kpc): \( \Omega \sim 50\text{km/s/kpc} \), gas transportation: disk \( \Rightarrow \) CMZ (central molecular zone)
  inner bar(~500pc): \( \Omega \gg 170\text{km/s/kpc} \) if it exists

  * the condition of the stability: \(|\Omega - \Omega_{\text{out}}| \gg \sim 120\text{km/s/kpc} \)
  gas transportation CMZ\( \Rightarrow \)within 20pc

→ Existence of an inner bar? \( \Leftrightarrow \) suggestion of existence by the spatial distribution of stars

Kinematically independent? \( \Leftrightarrow \) Difference of angular speed of the figure rotation
**Scientific objective A-1-(ii)**

Small-JASMINE’s data will constrain models of the gravitational potential in the Galactic nuclear bulge region (within ~300pc or the Galactic centre) with the phase-space density of stars

* Galactic model: bar (Ferres model) + bulge (exponential profile) + disk (Sofue model) + dark halo (NFW) + supermassive black hole (see A.1.1 Appendix p.4)

**Bar potential with the figure rotation \( \Omega \)**

**Success criterion:** determine with a confidence level of more than 99.7% whether or not the difference between the velocity of the figure rotation of the gravitational potential in the Galactic nuclear bulge and that of the outer bar is larger than 120km/s/kpc.

*please refer to the appendix A.1.1*
Scientific objective A-1-(iii)

Clarify the birth places of 4 classical Cepheid stars* by the trajectories of these stars and determine the rotation curve within the Galactic nuclear bulge by the use of these classical Cepheid variable stars if these stars orbit on the disk.

*Ref. Matsunaga, 2015ApJ...799...46M

The orbits of the Cepheids should be investigated once the proper motions become available, and a detailed study on their kinematics would provide important clues on stellar formation and dynamical evolution in the nuclear stellar disk around the Galactic center.

Success criterion: determine the tangential velocities (the component of the velocities perpendicular to the line-of-sight) of these stars with precisions similar to the present precisions of the radial velocities (~1.0 km/s).

*please refer also to the scientific objective A-4 and the appendix A.1.1.
Scientific objective A-2

Clarify formations of stars and star clusters around the Galactic nuclear bulge

*The Galactic nuclear bulge contains stars with ages ranging from a few million years to over a billion years, and young star clusters very near the Galactic centre, yet its star formation history and the triggering process for star formation remain to be resolved.
2.1 Science Goals and Mission Requirements / Scientific Objectives / Formation of Stars and Star Clusters in the Galactic Nuclear Bulge / Hidden Remnants

**Scientific objective A-2-(i)**

Galactic nuclear star clusters will be a key to understand the formation process of stars around the Galactic centre. There is possibility that the Galactic nuclear bulge have hidden remnants of star clusters. Hence it is interesting and important to find hidden remnants and enlarge the number of samples of the clusters.

**Success criterion:** discover cluster remnants by identifying the member of the cluster. *please refer to the appendix A.1.2.*
2.1 Science Goals and Mission Requirements / Scientific Objectives / Formation of Stars and Star Clusters in the Galactic Nuclear Bulge / Quintuplet & Arches

**Scientific objective A-2-(ii)**

Clarify the formations of young massive star clusters found in the Galactic centre region, such as Quintuplet and Arches clusters.

**Success criterion:** determine the birth places of Quintuplet and Arches clusters with the position error similar to the typical cluster size. (≈2.0pc).

*please refer to the appendix A.1.2.*
2.1 Science Goals and Mission Requirements / Scientific Objectives / Formation of Stars and Star Clusters in the Galactic Nuclear Bulge / HVS

Scientific objective A-2-(iii)

Finding hyper velocity stars (HVSs) near the Galactic centre (GC) will be a key to understand the origin of HVSs and S-stars which are young stars orbiting very near Sgr A*.

Stellar binary + SMBH

or single star + IMBH-SgrA* binary

Success criterion: search the HVSs by the measurement of the proper motions of stars within the Galactic nuclear bulge and verify the hypothesis that the birth place is near the Galactic centre (within 0.1 pc).

*please refer to the appendix A.1.2.
2.1 Science Goals and Mission Requirements / Scientific Objectives / Compact Objects

**Scientific objective A-3**

*Investigate compact objects around the Galactic nuclear bulge*

*The compact objects such as neutron stars, black holes are very interesting and important targets to understand the universe. They are much related in the activities of the Galaxy and star formations (birth rate and initial mass function, etc.) , which affect the evolution of the Milky Way Galaxy. In particular, BHs with mass of about 30 solar mass are found by the gravitational waves and so it is very interesting to clarify the origin of such massive BHs. Precise astrometry detect such BHs by the astrometric microlensing effect.

The X-ray sources are accreting compact objects in binary systems. Precise astrometry of these X-ray binaries provides a unique opportunity to obtain quantities which are very difficult to obtain otherwise.
2.1 Science Goals and Mission Requirements / Scientific Objectives / Compact Objects / BH

**Scientific objective A-3-(i)**

Detect the compacts objects by the astrometric microlensing effect to clarify physical characters of the compact objects

Success criterion: Search astrometric microlensing events and detect at least one event within the operation time with $3\sigma$ confidence level. In particular, search massive BHs with 30 solar mass(#) (which may be a primordial black hole) by the use of astrometric microlensing effect.

# a few massive BHs with ~ 30 solar mass were found by the gravitational wave (advanced LIGO)

*please refer to the appendix A.1.3.

# whether the event rate of lens effect by massive BHs with 20 ~ 30 solar mass is lager than the expected mean rate or not ➔ the origin of such BHs
2.1 Science Goals and Mission Requirements / Scientific Objectives / Compact Objects / X-ray Binary

Scientific objective A-3-(ii)

Clarify physical characters of the compact objects in X-ray binary systems.

Success criterion: Detect X-ray binary systems with red giants (symbiotic X-ray binaries) with $3\sigma$ confidence level and measure the distances of the binaries.

*please refer to the appendix A.1.3.
2.1 Science Goals and Mission Requirements / Scientific Objectives / Stellar Physics and Interstellar Medium

Scientific objective A-4

Understand stellar physics and interstellar medium

*It is very important and necessary to measure the distances of stars to clarify physical characters such as the absolute brightness, absolute energy radiated from the stars and then understand the stellar structures and evolutions. Furthermore the absolute brightness of stars in addition to the chemical components of the stars allow us to analyse the age of the stars, star formation rates which bring us the important information of the evolution of the Milky Way Galaxy.
Scientific objective A-4-(i)

Classical Cepheid variable stars are found to be one of good distance indicators by using the period-luminosity relation. Four classical Cepheid variable stars are found in the Galactic nuclear bulge and then it is important to verify the precision of the distances estimated by the period-luminosity relation in comparison with the distances measured by the annual parallaxes.

Success criterion: Calibrate the distances of four classical Cepheid variable stars derived by the period-luminosity relation with 10% error.

*please refer to the appendix A.1.4.
Scientific objective A-4-(ii)

Mira variable stars also are found to be one of good distance indicators by using the period-luminosity relation. At least 1000 Mira variable stars exit in the Galactic nuclear bulge and then it is important to verify the precision of the distances estimated by the period-luminosity relation in comparison with the distances measured by the annual parallaxes and make a 3-dimensional map of the magnetic field on the Galactic plane by combining measurements of polarization of light radiated from Mira variables whose distances are measured by the annual parallaxes.

Success criterion: Calibrate the distances of the Mira variables (the number is about 1000 in the survey region (1) and the survey region (2). Furthermore make a 3-dimensional map of the magnetic field on the Galactic plane.

*please refer to the appendix A.1.4.
Scientific objective A-4-(iii)

It is very important and necessary to measure the distances of stars to clarify physical characters such as the absolute brightness, absolute energy radiated from the stars and then understand the stellar structures and evolutions.

Success criterion: Determine the distances of each star measured in the Galactic nuclear bulge to investigate physical characters of each star.

*please refer to the appendix A.1.4.
2.2 Science Goals and Mission Requirements / Second Objectives for Open Use Program

B. **Astrophysics in different directions to the direction of the Galactic nuclear bulge**

Open use time (in summer and winter seasons):
50% or less than 50% of the total observation time
Good candidates: phenomena with short periods, bright objects in infrared bands

B-1. Compact celestial objects

Determination of orbital element of X-ray binaries and γ-ray binaries

⇒ Big revolution! ⇒ physics of accretion disks and jets, etc.

* a good candidate of X-ray binary: Cyg X-1: (l=71°, b=+3°)
  period: 5.6 days (unmeasurable by Gaia) companion star: m_v~9mag,
  change of the position: 40~50μas measurable by Small-JASMINE

⇒ identification of compact objects

* γCas: WD or NS⇒1σ degree of confidence, HESS J0632: NS or BH (2σ)

B-2. Extra-solar planets

detection of planets by astrometric method

* determination of mass with precisions of <20% for stars measured by radial velocities
* primary star: low-mass star (late M-dwarf, brown dwarf): H=10mag, V=16-18mag

6σ detection! Refer to appendix A.1.5

B-3. bright stars (<3.5mag)

* Roughly 130 stars brighter than 3.5mag are good science targets because it is very hard for Gaia to measure these stars with good precisions due to calibration issues.

B-4. Analysis of stellar hot spots
2.3 Science Goals and Mission Requirements / Mission Requirements

“The main scientific objective” means the objective which directly leads to mission requirements.

Here the main scientific objectives are objectives (A) on astrophysics in the Galactic nuclear bulge, which are shown in 2.1

“The mission requirements” describe items of the mission performance which must be satisfied to attain the scientific objectives with better precision that defined by the success criteria set in advance.

For example, the mission requirements are related to the survey regions, the number of stars measured during the mission, and the necessary measurement precisions.

*In addition to the main scientific objective, Small-JASMINE has a lot of secondary scientific objectives (B).
These secondary objectives have no direct impact on the mission requirements except for requirement for scientific operation. But these objectives can be attained as long as the mission requirements are satisfied through the accomplishment of the satellite system requirements.
### Science objectives + success criteria ➔ Mission data requirement

<table>
<thead>
<tr>
<th>Science objectives</th>
<th>Success criterion (nominal)</th>
<th>Mission data requirements</th>
</tr>
</thead>
</table>
| 1. Characterize the dynamical structures of the Galactic nuclear bulge to clarify energy sources fed into the Galactic centre and investigate the evolution of the Galactic nuclear bulge | (i) Verify the hypothesis that some supermassive black holes fall into the Galactic centre by the dynamical friction to form Sgr A* and so determine with more than 99.7% confidence level whether or not both the density and the velocity dispersion profiles of bulge stars within 100 pc from the Galactic centre correspond to the profiles heated up by the effect of dynamical friction due to the infall of some supermassive black holes.  
   (ii) Clarify the gravitational potential field in the Galactic nuclear bulge, in particular, the velocity of the figure rotation of the potential and so determine with a confidence level of more than 99.7% whether or not the difference between the velocity of the figure rotation of the gravitational potential in the Galactic nuclear bulge and that of the outer bar is larger than 120 km/s/kpc.  
   (iii) Clarify the birth places of 4 classical Cepheid stars by the trajectories of these stars and determine the rotation curve within the Galactic nuclear bulge by the use of these classical Cepheid variable stars if these stars orbit on the disk. Hence determine the tangential velocities (the component of the velocities perpendicular to the line-of-sight) of these stars with precisions similar to the present precisions of the radial velocities (∼ 1.0 km/s).  
   * please refer to the scientific objective 4 | Survey region (1):  
   the circle with a radius of 0.7 degree around the Galactic centre  
   Parallax error: ≤ 20 μas  
   Proper motion error: ≤ 200 μas/yr (for the region 1)  
   * It should be remarked that the achievement of the parallax error results in the achievement of the proper motion error of ≤ 20 μas/yr  
   Number of observable bulge stars within the survey region: ≥ 3500  
   Survey region (2):  
   Galactic longitude -2 ~ 0.5 degree  
   Galactic latitude 0.2 ~ 0.5 degree  
   Parallax error: ≤ 20 μas  
   Proper motion error: ≤ 150 μas/yr (for the region 2)  
   * It should be remarked that the achievement of the parallax error results in the achievement of the proper motion error of ≤ 20 μas/yr.  
   Number of observable bulge stars within the survey region (2): ≥ 2000  
   Survey region must include the target Cepheid stars  
   * the survey region required is found to be located within the survey region (1).  
   Proper motion error for four classical Cepheid variable stars: ≤ 25 μas/yr (which corresponds to the velocity error of 1 km/s at 8 kpc) |
<table>
<thead>
<tr>
<th>Science objectives</th>
<th>Success criterion/nominal</th>
<th>Mission data requirements</th>
</tr>
</thead>
</table>
| 2. Clarify formations of stars and star clusters around the Galactic nuclear bulge | (i) Galactic nuclear star clusters will be a key to understand the formation process of stars around the Galactic centre. Hence it is interesting and important to find hidden remnants and enlarge the number of samples of the clusters. So discover cluster remnants by identifying the member of the cluster.  
(ii) Clarify the formations of the young massive star clusters found in the Galactic centre region, such as Quintuplet and Arches clusters and so determine the birth places of Quintuplet and Arches clusters with the position error similar to the typical cluster size.  
(iii) Finding hyper velocity stars (HVSs) near the Galactic centre (GC) will be a key to understand the origin of HVSs and S-stars which are young stars orbiting very near Sgr A*. So search the HVSs by the measurement of the proper motions of stars within the Galactic nuclear bulge and verify the hypothesis that the birth place is near the Galactic centre (within 0.1 pc). | Survey region must be within the Galactic nuclear bulge  
Parallax error: $\leq 25\mu$as  
Proper motion error: $\leq 20\mu$as/yr (typical velocity dispersion of internal motions of stars in a star cluster is about $200\mu$as/yr and so the proper motion error of $\leq 20\mu$as/yr means that we can measure the velocity of the intrinsic motions of each star with the precision of 10% of the dispersion. This makes it possible to identify the members of the cluster with an unprecedented precision.)  
Survey region must be within the Galactic nuclear bulge  
Proper motion error: $\leq 26\mu$as/yr (a star cluster with the proper motion of $5\mu$as/yr can be back to the birth place ~4M years ago with the position error of $4pc$ (~the typical size of the star clusters).) |
### 2.3 Science Goals and Mission Requirements / Mission Requirements

<table>
<thead>
<tr>
<th>Science objectives</th>
<th>Success criterion (nominal)</th>
<th>Mission data requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Understand stellar physics and interstellar medium</td>
<td><em>(i)</em> Classical Cepheid variable stars are found to be one of good distance indicators by using the period-luminosity relation. Four classical Cepheid variable stars are found in the Galactic nuclear bulge and then it is important to verify the precision of the estimated distances as the distance indicator in comparison with those measured by the annual parallaxes. Hence calibrate the distances of four classical Cepheid variable stars derived by the period-luminosity relation with 10% error.</td>
<td>Survey region must include the target Cepheid stars (<em>^ the survey region is required to be located within the survey region (1).</em> ) Parallax error: $\leq 25 \mu$as $$(25/\sqrt{4-12.5 \mu} \text{ as } 10% \text{ error of the distance at } 8 \text{kpc})$$</td>
</tr>
<tr>
<td></td>
<td><em>(ii)</em> Calibrate the distances of the Mira variables (the number is about 1000 in the survey region (1) and the survey region (2). Furthermore, make a 3-dimensional map of the magnetic field on the Galactic plane.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>(iii)</em> It is very important and necessary to measure the distances of stars to clarify physical characters such as the absolute brightness, absolute energy radiated from the stars and then understand the stellar structures and evolutions. So determine the distances of each star measured in the Galactic nuclear bulge to investigate physical characters of each star.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Parallax error: $\leq 25 \mu$as</td>
</tr>
<tr>
<td>Second objectives in the survey mode for open use: Examples</td>
<td>Each success criterion depends on each scientific objectives selected among proposals for open-use program.</td>
<td>Scientific operation in summer and winter seasons toward directions of target objectives selected among proposals for open-use program.</td>
</tr>
<tr>
<td>Clarify X-ray binaries and γ-ray binaries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarify planets by astrometric microlensing effect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarify stellar hot spots</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarify physical characters of bright stars ($&lt; 8.5 \text{ mag}$) in binary systems</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3 Science Goals and Mission Requirements / Mission Requirements

<table>
<thead>
<tr>
<th>Science objectives</th>
<th>Success criterion(nominal)</th>
<th>Mission data requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission requirements as a whole</td>
<td>Survey region:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1) the circle with a radius of 0.7 degree around the Galactic centre</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2) Galactic longitude: 2~0.5 degree</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Galactic latitude: 0.2~0.5 degree</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parallax error:</td>
<td>&lt;=20μas</td>
</tr>
<tr>
<td></td>
<td>Proper motion error:</td>
<td>&lt;=20μas/yr</td>
</tr>
<tr>
<td></td>
<td>Number of observable bulge stars within the survey region(1):</td>
<td>&gt;=3500</td>
</tr>
<tr>
<td></td>
<td>Number of observable bulge stars within the survey region(1):</td>
<td>&gt;=2000</td>
</tr>
</tbody>
</table>
2.3 Science Goals and Mission Requirements / Mission Requirements

Scientific objectives (+ Success criteria)
⇒ the mission requirements are given as follows

Measure the time variations of stellar positions on the celestial sphere towards the direction of the Galactic nuclear bulge in a near-infrared band.

Requirement (i)
Survey region ⇒ the circle with a radius of 0.7 degree around the Galactic centre
Parallax error: <~20μas
Proper motion error: <~20μas/yr
the number of observable bulge stars within the survey area: >~3500

Requirement (ii)
Survey region: Galactic longitude -2 ~ 0.5 degree
Galactic latitude 0.2 ~ 0.5 degree
Parallax error: <~20μas
Proper motion error: <~20μas/yr
the number of observable bulge stars within the survey area: >~2000

Requirement (iii)
Make a catalogue which includes the time-series data of the stellar positions on the celestial sphere, parallaxes, proper motions and some physical properties derived from the time-series data, and release the catalogue to the worldwide public.
Additional scientific outputs expected by Small-JASMINE!!

Plan for investigations on scientific outputs at Mission Definition Phase

- investigations with science communities in Japan
  - With theoretical astrophysics group: Numerical simulations of the bulge, astrometric microlensing, exoplanets, etc. Baba, Kawata, Hattori, Fujii, Tagawa, Tanikawa, Umemura, Asada, Yamaguchi, et al.
  - With infrared astronomy group: stellar motions at the galactic nuclear bulge, variable stars, etc. Nishiyama, Matsunaga, et al.
  - With radio astronomy group: combination of gas motions and stellar motions, etc. Tsuboi, Oka, Miyoshi, Sakai, et al.

- investigations with international science communities
  - With space astrometry missions groups: synergy with Gaia, Theia and GaiaNIR (~2035). <= MoU between Small-JASMINE and Theia C. Boehm et al., D. Hobbs et al.
  - With the ZAH-ARI Gaia team (Heidelberg University): science cases for bright stars U. Bastian, M. Biermann, W. Löffler
  - With APOGEE-2 group: synergy with spectroscopic survey of the bulge <= MoU between Small-JASMINE and APOGEE-2 S. Majewski, et al.
  - With WFIRST group: synergy with the microlensing fields, etc. S. Gaudi, T. Sumi, et al.
The Theia collaboration has made a report on science cases for Small-JASMINE, which includes the following scientific objectives:

1. Is Dark Matter made of PBHs?
2. Constraining the potential well of Dwarf Spheroidal Galaxies
3. Constraining dark matter substructures in galaxies with strong lensing
4. Compact objects
5. From stellar to supermassive Black Holes
6. The Frontier of Exoplanet Astrophysics
7. ORBIT AND MINERALOGY MAPPING OF ASTEROIDS
Synergy with other missions such as BRAVA, APOGEE-2, and WFIRST missions

Cooperation with BRAVA and APOGEE-2(S) results in very strong synergy for studies of the Galactic bulge.

Information of radial velocities, chemical composition and photometry (in other bands) is complementary to Small-JASMINE for the scientific targets in the Galaxy.
2.5 Science Goals and Mission Requirements / Synergy with other Missions

★BRAVA: The Bulge Radial Velocity Assay (PI. M.Rich)

Overview: BRAVA is a large-scale radial velocity survey of the Galactic bulge. The aim of this survey is to advance the scientific knowledge of how our Galactic bulge and Milky Way formed. This can be done by using the radial velocities from the BRAVA stars surveyed to test and constrain dynamical models of the bulge, and to quantify the importance, if any, of cold stellar streams in the bulge and its vicinity.

Strategy: Use M giants as dynamical tracers and from the stellar dynamics, learn about our bulge. M giants are brighter than clump giants and can be observed in high extinction fields. Select M giants from the 2MASS survey. Hence they have excellent, uniform astrometry and photometry; ease of developing links to spectra for a public database. Use cross correlation from 7000 - 9000 Angstroms (include Ca IR triplet) to very accurately determine the stars radial velocity. To observe these M giants, use 3x10 min exposures with the Hydra fiber spectrograph on the Blanco 4m telescope at the Cerro Tololo Inter-American Observatory (in Chile); about ~100 stars/field at R~4000 can thus be obtained. Radial velocities have been determined for 9,000 stars to date.

BRAVA has already brought us very interesting results on the Galactic bulge ➔ compliment of Small-JASMINE for investigations of Galactic bulge.
APOGEE survey: High-resolution H-band spectroscopic survey
2.5m telescope at the Apache Point Observatory
APOGEE-1 (SDSS-III):
100,000 giants to magnitude H=12.5, Bulge stars: 7000
R~20000-30000, S/N~100, Wavelength 1.52-1.69mm, velocity error 0.5 km/s
15 elements error of 0.1 dex

APOGEE-2 (SDSS-IV) ➔ The same instrument as that of APOGEE-1 will be set at Las Canpanas Observatory

~90,000 stars in the bulge

MoU for powerful scientific collaboration between APOGEE-2, SDSS-IV collaboration and Small-JASMINE has been concluded.
**WFIRST**: a NASA observatory designed to perform wide field imaging and surveys of the near-infrared (NIR) sky.

- 2.4m telescope (already exists)
- NIR instrument with 18 H4RG detectors
- Baseline exoplanet coronagraph
- 6 years life time
- Launch date: ~2025

<table>
<thead>
<tr>
<th>Imager</th>
<th>0.76-2.0 microns 0.28° FoV, 0.11&quot; pixel scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters:</td>
<td>z (0.76 - 0.98), Y (0.93-1.19), J (1.13-1.45), H(1.38-1.77), F184 (1.68-2.0), W149 (0.93-2.00)</td>
</tr>
</tbody>
</table>
Microlensing Fields

Properties.
- ~3 sq. deg (10 fields).
- ~432 days (6 seasons of 72 days each).
- ~15 minute cadence, 52s in W149.
- ~12 hour cadence, 290s for Z087.
- ~85% of the area will have ~40,000 measurements per star ($N^{-1/2} = 1/200$).
- ~60 million stars down to $H_{AB} < 21.6$.
- 2 million seconds of integration time.
- ~2.5 billion photons detected for a $H_{AB} = 19.6$ star

By S. Gaudi

Similar observation to that of Small-JASMINE
Astrometry may be possible by the use of the data in the Microlensing Fields

Note: However, the expected precisions of astrometric parameters which are estimated by taking the systematic errors into account have not been disclosed yet.

*Large telescope (2.4m) ➔ small diffraction limit and small photon noise: Good!
*But, we have concerns about systematic noises.
WFIRST is not dedicated to astrometric measurement and so the instruments of WFIRST do not seem to be optimized for astrometry.

*precise estimate of centroid of stellar image
  ➔ PSF: necessary to spread over about a few pixels
*high thermal stability of telescope structures is required
  (variation of stellar images should be less than 10μas on the focal plane within a few ten minutes.)
*stability of detector sensitivity affected by cosmic radiation
*stability of array of 18 detectors
If 10 μas-level precisions of astrometric parameters can be realised by WFIRST, then we will have strong synergy of scientific collaboration between WFIRST and Small-JASMINE.

Survey regions of both missions are complementary to each other.

Figure 1: The two Small-JASMINE target regions near the Galactic centre: a centred circular target with a radius of 0.7° and a rectangular off-centre target with 0.3°×2.5°. Coloured 2MASS image.
Furthermore, we can submit a proposal for WFIRST Guest Observation program and add a survey filed near the survey region of Small-JASMINE as necessary. This part can be obviously reduced because WFIRST uses a primary mirror with larger aperture size. This part corresponds to the systematic errors such as the errors caused by the instability of thermal structures of the instruments.

Launch date of WFIRST: ~2025
Launch date of Small-JASMINE: ~2024

If we have guest observations in a field overlapping both, the microlensing field and the survey area for Small-JASMINE, the overlapping time of observational operations will improve the calibration and validation of data provided by both missions and will also improve the promotion of scientific outputs.

*provided that the systematic errors in WFIRST are the same as those planned in Small-JASMINE → WFIRST guest observation time needs ~0.8 month / 1FOV to attain the same precision of the parallaxes as that of Small-JASMINE.

Anyway, if WFIRST will provide 10μas-level precisions of astrometric parameters (however, attainable precisions are still unclear now), we will have strong synergy between the scientific collaborations by combining the information in the fields measured by each mission.
Supplement
1.1 Mission Overview/Astrometry

**Space Astrometry Mission**

Astrometry: Fundamental task of measuring stellar positions on the celestial sphere

Repeated measurements

- **Trajectory of a star: Helical motion**
  - annual parallactic ellipse + proper motion (straight line)
  - annual parallax of the star
  - distance of the star

2D-positions of stars

Distance of the star × tangential velocity of the star
1.1 Mission Overview / Astrometry

★Residual motions from the helical motion → Very important information!

Binary systems, Planetary systems, Gravitational lens effects, effects of stellar hot spots, etc.

Residual motions

Physical characters such as mass of binary stars, mass of planets, physical characters of gravitational lens objects, etc.

*Binary or planetary systems

*Gravitational lens effect

Recent topics: HST has for the first time in the world detected astrometric microlensing outside the solar system!

⇒ The mass of WD has been determined

(Sahu et al. Science 356, 1045, 2017)
Astrometry missions provide the following items:

- True brightness of stars, true energy emitted by stars
- Base of the distance ladder: estimate the distances of celestial objects far away from us.
- The size, shape, structural elements, etc. of the Milky Way Galaxy, the size, shape etc. of star clusters
- (together with radial velocities) 3-dimensional velocities of stars and star clusters => the birth places of stars and star clusters
- Information about the gravitational field and/or phase-space density distribution * dynamical structures, orbits of (unobservable) stars and dark matter
- Tracing the formation and evolution of star clusters or the Galaxy
- Orbital elements and physical characteristics of binary systems, survey of exoplanets, physical characteristics of exo-planets, physical characteristics of gravitational lenses, etc.

We can see “invisible” things.

Annual parallax

Position on the celestial sphere + distance

3-dimensional distribution of stars

Proper motion + distance

Tangential velocity of stars

3-dim spatial and 3-dim velocity distributions of stars

Spatial motions (residuals from the helical motions)
1.2.1 Mission Overview / Outline of SJ / Key Project

The number density of observable stars (Hw<12.5mag) estimated by the use of the combination of 2MASS and the Guide Star Catalogue (GSC)

<table>
<thead>
<tr>
<th>Galactic longitude</th>
<th>The number of stars / (0.1deg × 0.1deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>173 179 198 198 177 136 282 298 248 221 218 283 231 208 273 190 133 153 160 190 219 231 265 305 287 276 304 259 231 157 153 170 136 167 155 152</td>
</tr>
<tr>
<td>0.7</td>
<td>143 148 182 150 120 157 241 264 283 162 122 146 181 168 182 95 71 58 49 108 188 229 241 276 267 249 239 217 226 162 163 250 193 217 215 168</td>
</tr>
<tr>
<td>0.8</td>
<td>126 165 141 121 126 216 215 187 209 184 111 67 80 133 120 43 40 17 23 47 125 172 197 231 258 278 226 183 198 160 131 179 143 120 106 84</td>
</tr>
<tr>
<td>0.5</td>
<td>91 86 89 114 203 183 162 139 121 73 114 46 59 61 53 15 27 31 29 56 104 139 175 204 220 206 256 197 160 133 89 132 147 201 134 97</td>
</tr>
<tr>
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</tr>
<tr>
<td>0.3</td>
<td>42 56 94 129 89 82 35 60 64 24 29 41 29 61 60 28 31 22 29 47 68 48 75 110 185 200 197 191 120 135 77 111 105 128 71 82</td>
</tr>
<tr>
<td>0.2</td>
<td>39 47 59 73 66 48 59 58 68 25 35 17 30 60 61 31 19 23 38 49 79 38 89 93 137 127 142 108 90 101 63 47 55 47 42</td>
</tr>
<tr>
<td>0.1</td>
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</tr>
<tr>
<td>0</td>
<td>45 55 43 36 54 59 53 28 29 27 19 21 31 32 28 21 19 16 14 18 48 34 24 51 80 57 41 46 52 31 34 35 17 47 49 36</td>
</tr>
</tbody>
</table>

-0.1 | 43 46 29 50 61 47 28 34 28 33 23 31 44 33 35 15 19 23 23 32 32 37 38 47 63 80 60 60 53 54 63 22 39 30 36 25 35 73 |
-0.2 | 63 59 52 55 45 38 42 32 35 23 38 44 69 38 25 36 28 26 31 32 29 48 68 87 72 92 92 76 36 31 31 27 45 40 20 33 61 |
-0.3 | 80 63 70 56 47 38 32 52 39 52 40 42 71 62 28 42 42 37 35 69 59 47 36 63 41 50 42 49 35 54 39 29 27 45 36 51 |
-0.4 | 125 102 98 71 47 78 51 35 46 49 38 59 38 42 43 31 45 45 26 55 67 67 34 50 60 31 35 32 50 29 28 39 32 41 72 87 46 |
-0.5 | 170 189 123 154 51 79 64 37 40 50 37 45 61 64 63 51 51 55 61 70 41 52 49 33 34 34 25 25 31 23 51 59 70 79 52 |
-0.6 | 256 256 222 181 94 47 65 141 97 70 70 99 57 93 108 76 46 58 33 67 90 49 39 35 33 37 28 34 38 42 48 58 88 120 66 50 54 |
-0.7 | 356 325 225 209 123 80 101 156 204 70 154 170 100 152 165 89 58 52 65 117 109 45 40 45 42 22 52 30 20 46 58 116 140 95 56 84 |
-0.8 | 387 347 270 273 110 103 245 222 198 136 278 227 222 187 173 190 111 55 56 58 58 81 46 30 36 39 39 12 52 59 57 64 63 108 128 112 92 87 |
-0.9 | 486 386 396 333 121 151 220 260 252 283 289 285 288 224 216 229 204 92 98 123 108 63 86 79 78 91 83 93 90 83 61 77 92 121 149 118 |
A.1.1 Appendix / Science Goal / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / SMBH / Universal Profiles

- Overview

- Summary of simulation results

- Explanation

- Origin of the energy release
The radius of a heated up profile formed by the merging of supermassive BHs is about 100pc independently of the number of BHs and initial power index of the density distribution of bulge stars, γ.

Reason

The total mass of the stars located within the radius of 100pc from the Galactic centre (hereafter central mass) is larger for larger γ. (see Tanikawa and Umemura 2014, Merritt et al. 2004, the figures in p24)

$\Rightarrow$ In order to form a heated up profile with a radius of about 100pc, more energy provided by the gravitational potential of BHs (see p.25 and p.26) for scattering the bulge stars must be released for larger γ, because a larger total mass must be transferred from around the centre to outer regions.

$\Rightarrow$ When the central mass density is higher (for larger γ), the mean separation of the bulge stars at the central region is smaller, and so the distance to BHs will also be smaller. Therefore a larger amount of binding energy of BHs will be released due to the smaller distance between the two BHs.

BS=bulge star: stars within the region of bulge excluding BHs.
Numerical simulations show evidence that the heated up profiles with a radius of about 100 pc are formed for any initial power index $\gamma=0.5\sim2$ of the density distribution, i.e. the values expected for bulges by numerical simulations without supermassive BH when BHs are merging around the Galactic centre (Tanikawa & Umemura 2014 and Merritt et al. 2004).

**Summary of simulation results**

- **①** When $\gamma=1$
  (Tanikawa private communication, see p.22)

  The simulation results show that the radius of the heated up profile will be extended to about 100 pc (see the right figure).

- **②** Relation between $\gamma$ and the radius of the heated up profile (Merritt et al. 2004, see p.7 and p.8)

  Merritt et al. 2004 show that the radius of the heated up profile is about 100 pc regardless of the initial power index of $\gamma=0.5\sim2$ (see the next slide).

**The radius of the heated up profile is about 100 pc (independently of the initial power index of $\gamma=0.5\sim2$).**
The numerical simulations (Tanikawa & Umemura 2014) show that the radius of the heated up profile extended to about 0.05 $r_g$ which corresponds to 100 pc in radius, where $r_g$ is the virial radius.

• $\rho_g$ is average density within $r_g$. 

Detailed Explanation

Tanikawa & Umemura 2014
The radius of the heated up profile: $r_c$
- When $\gamma=2$, $r_c \sim 0.1a \sim 0.1Re$
- When $\gamma=1$, $r_c \sim 0.2a \sim 0.1Re$
In any case, about 0.1 of the effective radius shown below

$\gamma$: power index at the central region $\rho \propto r^{-(\gamma)}$
$a$: density scale length
$Re$: effective radius
(radius of projected density including the half of the mass.)

$Re/a=(1.8,1.3,1)$ for $\gamma=(1,1.5,2)$
Detailed Explanation

Merritt et al. 2004

More central mass is transferred from around the Galactic centre to outer regions when the power index, $\gamma$, is larger.

For example, mass deficit is about $3M_{\text{BH}}$ at $t=1000$ for $\gamma=1$ while $4.5M_{\text{BH}}$ at $t=1000$ for $\gamma=1.5$ and $6M_{\text{BH}}$ at $t=1000$ for $\gamma=2$.

As a result, the radius of the mass deficit is almost constant for various $\gamma$.

**Mass deficit**: Mass difference between the initial stellar density and the density at time $t$, integrated from the origin out to the radius at which $\rho(r,t)$ first exceeds $\rho(r,0)$.
Origin of the energy release

Single BH with $10^6$ solar masses

• A single BH does not have sufficient energy to extend the radius of the heated up profile to 100pc.

Reason

Single BH: Potential energy is transferred only from the BH to the bulge stars (BH-BS).

Many BHs: In the first stage, it is mainly the binding energy between the individual BHs and the surrounding bulge stars (BH-BS) which is released by scattering away some of the bulge stars. At this stage, this BH-BS binding is the main contribution to the Galactic nuclear bulge region's overall energy release. At later stages, the binding energy released by the infall of the BHs towards the Galactic centre and by closing their mutual distance (BH-BH) becomes the main contribution to the overall energy release of the Galactic nuclear bulge region. This BH-BH binding energy release continues until the separation between the BHs approaches the mean separation between the surrounding bulge stars.

The simulation results mentioned above are shown on the next slide.
BH-BH binary systems mainly contribute to the release of the energy from BHs to bulge stars. (Energy of BH-BH binary systems > Energy of BS-BH)

Total energy of BHs decreases (pink symbols in the right figure). ⇒ BHs can supply energy to the field stars constantly.

This figure shows the simulated time evolution of the total potential energy of the BHs (pink symbols in the figure). In the 1st stage (see time from 0 to 20 in the figure) it follows the evolution of the BH-BS binding energy (red circles in the figure). This means that the overall potential energy is dominated by the BH-BS binding. In the 2nd stage (see time larger than 20) the BH-BS energy flattens out and becomes mostly independent of time while the overall potential energy continues to decrease. Since the total potential energy is the sum of the BH-BS and the BH-BH binding energies, this means that the main energy release in the 2nd stage must come from the BH-BH binding.

BS: Bulge Star
BH: Black hole

A.1.1 Appendix / Science Goal / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / SMBH / heated up profiles
Summary

On the Effect of the dynamical friction by the large molecular cloud and the globular cluster.

Compared to a massive black hole, the radius of a cloud or a cluster is large.

⇒ The effect of scattering is small (about a quarter)

The main energy source for forming the heated up profile with a radius of 100pc is BH-BH binding energy.
Therefore the possibility of forming the heated up profile by a single molecular cloud or globular cluster is very small.
Large molecular cloud

Large molecular cloud (MC) with a mass of $M = 2\times10^5 M_\odot$ has been found (Matsumura, Oka et al. 2012).

We estimate whether the cloud affects the density distribution of the field stars. The parameters of the cloud are as follows (Matsumura, Oka et al. 2012):

- Mass: $M = 2\times10^5 M_\odot$
- Size: $L = 20$ pc

Time scale of the Dynamical friction

$$\frac{d\vec{v}_M}{dt} = -\frac{4\pi}{v_M^3} \ln(\Lambda) G^2 m(M + m) n_0 \left[ \text{erf}(X) - \frac{2X}{\sqrt{\pi}} e^{-X^2} \right] \vec{v}_M$$

where

$$\Lambda = \frac{b_{\text{max}} V_0^2}{GM(M + m)}$$

$$X = \frac{v_M}{\sqrt{2}\sigma}$$

Compared to the BH, the radius of the molecular cloud is large. Therefore the effect of scattering is small (about a quarter). The difference between the case of the cloud and that of BH is the value of $\ln \Lambda$

$$\Rightarrow \ln \Lambda(\text{MC}) \sim S \ \ln \Lambda(\text{BH})$$

$S = 1/4 \sim 1/3$
Globular cluster

Parameters:

- Mass: $M = 1 \times 10^6 M_\odot$
- Size: a few $\times 10$ pc

Radius of the globular cluster is as large as the molecular cloud. Therefore the effect of scattering is small (compared with BH, about a quarter).

The possibility of forming a heated up profile by a single BH is very small. A single BH does not have sufficient energy to make a heated up profile by dynamical friction.

Also, compared to the BH, effect of dynamical friction by a molecular cloud and a globular cluster is small (compared to BH, about a quarter).
Selection method for models
Kullback–Leibler (KL) divergence

- Scale of the distance between two probability distributions (the distance of $f_{\text{obs}}$ relative to $f_{\text{model,}\theta}$)
  (note: axiom of the distance is not satisfied)

\[ D_{KL}(f_{\text{obs}} \mid f_{\text{model,}\theta}) = \sum_i f_{\text{obs}}(i) \log \frac{f_{\text{obs}}(i)}{f_{\text{model,}\theta}(i)} \]

- $f_{\text{obs}}$: data, observation, true probability distribution etc.
- $f_{\text{model,}\theta}$: theoretical model etc.
- $i$: the index of the grid in the phase-space

- KL divergence represents the scale of the difference between $f_{\text{obs}}$ taken by the observation and a model, $f_{\text{model,}\theta}$.

If the model coincides with the observations, the KL divergence is equal to 0, otherwise it has a positive value which depends on the difference between model and observations.

Among a set of models, the model with the minimum of KL divergence is the one that model is most consistent with the observations.
How is it possible to fall the gas into the Galactic center?

- the scenario on the gas supply to the Galactic centre by the nested bars
  (Namekata et al. 2009)

Formation of the central molecular zone (CMZ) by the outer bar

Formation of circumnuclear gas disk and supply of the gas to the Galactic centre by the inner bar

the existence of the inner bar (<500 pc) at CMZ = Lindblad resonance
  - violent motion of the gas (shock wave)
  - supply of the gas to the galactic centre, explosion at the centre, formations of star clusters and stars?
Observational proof of the existence of the Inner bar

- The size of the bar \( \sim \) a few 100 pc

Spatial distribution of red clumps surveyed in K-band

Fig. 3. Contours of the residual density after subtracting the main component. Note that the asymmetry is in the opposite direction of the large scale Galactic Bar. Contours values: \((max, min) = (38000, 400)\) stars/sq deg.
What kind of cases do the gas fall into the Galactic center?

Whether or not the gas can fall into the Galactic centre is investigated by calculating the motion of gas by 2-dimensional fluid simulation for the case that the Galaxy has a rotating inner bar and the dependence of the result on the rotation velocity is also investigated.

Numerical results: rapidly rotating inner bar and/or the inner bar with large axial ratio make it possible for the larger amount of gas to fall into the Galactic centre (<20pc) than that for the case of no inner bulge.
Evaluation method for the reliability

1. Use a set of Galaxy models with different rotation angular velocities and axial ratios but with a rotation curve and radial velocity distribution which are consistent with observations.

   Construct the phase-space density distribution whose density profile and velocity distribution are self-consistent with those assumed a priori.

   (\(\Rightarrow\) by the use of M2M method)

   \(f(E_J, V_c)\)

2. Select the most suitable model by the comparison of the observed phase-space density with those given in some models by the use of KL divergence

\[ f_{\text{obs}}(x, v) \]

3. Calculate the correct-answer rate

4. Evaluate the necessary observational precision and the number of observable stars to get the reliability (correct-answer rate) of more than 99.7%  
   \(= \Rightarrow\) mission requirement
The Galaxy model used in this calculation

Inner core & bulge (Sofue 2013)

\[ \rho(r) = \rho_0 e^{-r/R_0} \]

Disk (McMillan 2011)

\[ \rho(R, z) = \frac{\Sigma_0}{2z_d} e^{-R/R_d} e^{-|z|/z_d} \]

Halo (McMillan 2011)

\[ \rho(r) = \frac{\rho_0}{r R_s \left( 1 + \frac{r}{R_s} \right)^2} \]

Ferrers bar (1877)

\[ \rho(x, y, z) = \begin{cases} \frac{105 M_{\text{bar}}}{32 \pi abc} (1 - m^2)^2 & 1 > m \\ 0 & 1 < m \end{cases} \]

\[ m^2 = \left( \frac{x}{a} \right)^2 + \left( \frac{y}{b} \right)^2 + \left( \frac{z}{c} \right)^2 \]
Dynamical model of the Galaxy used in this calculation

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black hole</td>
<td>$4.0 \times 10^6 M_\odot$</td>
</tr>
<tr>
<td>Core</td>
<td>$5.7 \times 10^7 M_\odot$</td>
</tr>
<tr>
<td>Bulge</td>
<td>$8.4 \times 10^9 M_\odot$</td>
</tr>
<tr>
<td>Disk</td>
<td>$1.4 \times 10^{10} M_\odot$</td>
</tr>
<tr>
<td>Halo</td>
<td>$1.4 \times 10^{12} M_\odot$</td>
</tr>
</tbody>
</table>

This Galaxy model is constructed to provide the observed global rotation velocity and the rotation curve within 1kpc.
Ferrers bar model

\[ \rho(x, y, z) = \rho_0 (1 - m^2)^2 \quad m < 1 \]
\[ \rho(x, y, z) = 0 \quad m \geq 1 \]

\[ m^2 = \left( \frac{x}{a} \right)^2 + \left( \frac{y}{b} \right)^2 + \left( \frac{z}{c} \right)^2 \]

Fluctuation of \( \Omega - \kappa / 2 \) according to the bar length
A.1.1 Appendix / Science Goal / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / Figure Rotation

Reference. Construction method for the phase-space density

Made to measure (M2M) method (Syer & Tremaine 1996)

Calculate orbits of many test particles in the given Galaxy model
Evaluate the weight of each particle (existence probability) to reconstruct the density profile and velocity distributions assumed a priori.
Each particle represents one torus which has a set of values of isolating integrals determined by the initial condition in the phase-space.
Hence the weight of a particle corresponds to the phase-space density distribution.

\[ \Delta \Phi(x) = 4\pi G \rho(x) \]

The density profile reconstructed by the orbits of test particles
In the given \( \Phi(x) \) is consistent to \( \rho(x) \) derived by \( \Phi(x) \) \( \Rightarrow \) Self-consistent

\[ W_1 \times + W_2 \times + W_3 \times + \cdots \]

\[ = \rho(x) \]

calculate \( w_n \) of all particles
A.1.1 Appendix / Science Goal / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / Figure Rotation

Construction of phase-space density distribution

Mass distribution

Box orbit

Error $\sim 10^{(-9)} \%$
Condition of figure rotation velocity for the existence of the stable inner bar

\[ L > \left| \int_0^{T/4} \dot{L} \, dt \right| \]

\[ L = r \times r (\omega_i - \omega_o) \]

\[ \dot{L} = f \times r \sin((\omega_i - \omega_o)t) \]

\[ \omega_i - \omega_o = \pm \sqrt{4.4G \rho} \]

\[ \omega_i - \omega_o \approx 117 [\text{km} / \text{s} / \text{kpc}] \]
A.1.1 Appendix / Science Goal / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / Figure Rotation

★ example of the calculation of the reliability

- True solution: rotation angular velocity = 170 km/s/kpc, a/b = 4
  * Existence of dynamically stable inner bar
    \[ |\Omega_{\text{in}} - \Omega_{\text{out}}| >> 120 \text{ km/s/kpc} \]
- Mock catalogue
  * Parallax error: 20~80 μas
  * Proper motion error: 50~400 μas/year
    ( * Radial velocity error: 2 km/s)
  * The number of observable stars: 1500 ~ 2500
  * Survey region: region 2

- Trial models
  model 1: Phase-space density of the true solution
  model 2: (e.g.) Rotation angular velocity
    \[ = 50 \text{ km/s/kpc} \text{ (which is the estimated value of the outer bar)} \], a/b = 4

- Reliability
  if \( X = KL(\text{observation and model } 2) - KL(\text{observation and model } 1) > 0 \) ➔ correct!
  Evaluate the number of times for \( X > 0 \) by the use of many samples.
Results of the confidence level tests for scientific objective A-1-(ii)

- **Number of observable stars**
  - More than 2000 stars
  - Confidence level: more than 99.7%

- **Parallax error** $\delta \pi [\mu\text{as}]$
  - Less than 20$\mu\text{as}$
  - Confidence level: more than 99.7%

- **Proper motion error** $\delta \mu [\mu\text{as/yr}]$
  - 150$\mu\text{as/yr}$
  - Confidence level: more than 99.7%

The mission requirement is met.
A.1.1 Appendix / Science Goal / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / Cepheid

Success criterion

Clarify the birth places of 4 classical Cepheid stars by the trajectories of these stars and determine the rotation curve within the Galactic nuclear bulge by the use of these classical Cepheid variable stars if these stars orbit on the disk. Determine the tangential velocities (the component of the velocities perpendicular to the line-of-sight) of these stars with precisions similar to the present precisions of the radial velocities (~1.0 km/s).

Mission requirement

Survey region must include the target Cepheid stars (* the survey region required is found to be located within the survey region(1).)

Matsunaga, 2015ApJ.799, 46M

These stars are suggested to be located at about 8 km. Hence the tangential velocity precisions of 1.0 km/s corresponds to ~25 μas/yr.
A.1.2 Appendix / Science Goal / Scientific Objectives / Dynamical Structure of the Galactic Nuclear Bulge / Hidden Remnants

Success criterion

Galactic nuclear star clusters will be a key to understand the formation process of stars around the Galactic centre. Hence it is interesting and important to find hidden remnants and enlarge the number of samples of the clusters. So discover cluster remnants by identifying the member of the cluster.

Mission requirement

Typical mass of the nuclear star cluster is about $10^4 \, M_{\odot}$. Typical size is about 1 pc. Hence typical velocity dispersion of internal motions of stars in a star cluster is about 200μas/yr and so the proper motion error of ~20μas/yr means that we can measure the velocity of the intrinsic motions of each star with the precision of 10% of the dispersion. This makes it possible to identify the members of the cluster with an unprecedented precision*.

$\Rightarrow$ Proper motion error: $0.1 \times 200\mu\text{as/yr}=20\mu\text{as/yr}$

Success criterion

Clarify the young massive star clusters found in the Galactic centre region, such as Quintuplet and Arches clusters and so determine the birth places of Quintuplet and Arches clusters with the position error similar to the typical cluster size.

Mission requirement

Survey region must include the above 2 star clusters.

*Stars in the clusters must be confirmed within the bulge region by the estimate of the distance.

\[ \text{Parallax error} < \sim 25 \mu \text{as} \] (see to the appendix A.1.6)

*the age of the Quintuplet cluster is about 4M years. When the star cluster goes back 4M years ago, the position error must be within 4pc \sim 100” \sim \text{the size of the star cluster}.

\[ \text{Proper motion error} : 100”/4 \text{M year} \sim 25 \mu \text{as/yr} \]
Success criterion

Finding hyper velocity stars (HVSs) near the Galactic centre (GC) will be a key to understand the origin of HVSs and S-stars which are young stars orbiting very near Sgr A*. So search the HVSs by the measurement of the proper motions of stars within the Galactic nuclear bulge and verify the hypothesis that the birth place is near the Galactic centre (within 0.1 pc ~ around the existence region S-stars’ orbits).

Mission requirement

*assumption: HVS is located 0.5 degree from the GC.

:the velocity of a HVS is 1000 km/s ~ 15mas/yr (constant)

⇒ if the birth place is the GC, then the age is 1800”/15 mas/yr ~ 0.12 M years

*the position error is within 0.1 pc(≈ 2.5”), 0.12M years ago.

⇒ Proper motion error: 2.5”/0.12M yr ~ 20μas/yr
A.1.3 Appendix / Science Goal / Scientific Objectives / Compact Objects / BH

Success criterion
Detect the compacts objects by the astrometric microlensing effect to clarify physical characters of the compact objects. So search astrometric microlensing events and detect at least one event within the operation time with $3\,\sigma$ confidence level. In particular, search massive BHs with 30 solar mass (which may be a primordial black hole) by the use of astrometric microlensing effect.

Mission requirement
Survey region: the survey region (1)+the survey region(2)

*assumption: the number of bulge stars~ 9000
  : effective operation time~1.5 years
  : average mass of lens objects ~0.5 solar mass
  : probability of observing a centroid shift within 1 year for a given observed star is given by Table 2 of Dominik and Sahu (ApJ, 2000) Please refer to p.102

Probability : $1.0/9000/1.5 \sim 7.4 \times 10^{-5} \Rightarrow$ centroid shift>60$\mu$as
3 $\sigma$ detection $\Rightarrow$ 60$\mu$as/3 $\sim$ 20$\mu$as
A.1.3 Appendix / Science Goal / Scientific Objectives / Compact Objects / X-ray Binary

Success criterion

Clarify physical characters of the compact objects in X-ray binary systems. In particular, detect X-ray binary systems with red giants (symbiotic X-ray binaries) with 3σ confidence level and measure the distances of the binaries

Mission requirement

\[ |\alpha| = 125[\mu as] \left( \frac{q}{0.2} \right) \left( \frac{a}{5\text{ au}} \right) \left( \frac{D}{8\text{ kpc}} \right)^{-1} \]

* \( q \sim 0.2 \) (=Mp/ M*, M* \sim 10 solar mass, Mp \sim 2 solar mass)
  D \sim 8\text{ kpc}
  a \sim 2.5 \text{ au} (0.6 \sim 5 \text{ au}) \quad (\text{period: } T=1.1\text{yr})
  \alpha \Rightarrow \sim 61\mu as
  3\sigma \text{ detection} \Rightarrow 61/3 \sim 20\mu as

Error of the measurement of the deviation is less than \sim 20\mu as (typical deviation is about 100\mu as) which corresponds to the requirement of the parallax of \sim 20\mu as
Survey region must include the target Cepheid stars
(* the survey region required is found to be located within the survey region(1).)

Matsunaga, 2015ApJ.799, 46M

Four Cepheid are located at about 8 kpc ~ 125 μas .
⇒ 10% error of calibration⇒ 12.5 μas
Four Cepheid variables⇒12.5 μas × √4 ~ 25μas
⇒ Parallax error of each target star : <~25μas
Success criterion

Calibrate the distances of the Mira variables (the number is about 1000 in the survey region (1) and the survey region (2)). Furthermore make a 3-dimensional map of the magnetic field on the Galactic plane.

Mission requirement

Calibrate the distances of the Mira variables (the number is at least 1000 in the survey region (1) and the survey region (2)).

Matsunaga, MNRAS 2009

*Stars must be confirmed within the bulge region by the estimate of the distance.

Parallax error: <~25μas (see to the appendix A.1.6) Please refer to p.94-95
A.1.4 Appendix / Science Goal / Scientific Objectives / Compact Objects / Stars

Success criterion

It is very important and necessary to measure the distances of stars to clarify physical characters such as the absolute brightness, absolute energy radiated from the stars and then understand the stellar structures and evolutions. So determine the distances of each star measured in the Galactic nuclear bulge to investigate physical characters of each star.

Mission requirement

*Stars must be confirmed within the bulge region by the estimate of the distance.

Parallax error: $<\sim 25\mu\text{as}$ (see to the appendix A.1.6) Please refer to p.94-95
Small-JASMINE can detect with 6 \( \sigma \) confidence level a Jupiter-like planet accompanied with a typical brawn dwarf at 10pc.

Deviation from the helical motion

\[
|\alpha| = \frac{M_p}{M_*} \frac{a}{d}
\]

\[
= 100[\mu \text{as}] \left( \frac{M_p}{M_J} \right) \left( \frac{M_*}{M_S} \right)^{-1} \left( \frac{a}{1 \text{au}} \right) \left( \frac{D}{10 \text{pc}} \right)^{-1}
\]

\( M_p \sim M_J \sim 0.001 \) solar mass
\( M_* \sim 0.08 \) solar mass \( \sim 80 \) \( M_J \)
\( a=0.1 \sim 1000 \text{ au} \Rightarrow 0.1 \text{ au}, D \sim 10 \text{pc} \) (period: \( T=0.11 \text{yr} \))
\( \alpha \Rightarrow \sim 125 \mu \text{as} \)

6\( \sigma \) detection \( \Leftarrow 125/20 \sim 6 \)

*error of the parallax is \( \sim 20\mu \text{as} \)

\( \Rightarrow \) error of the measurement of the deviation is \( \sim 20\mu \text{as} \)
Why do we need <~25μas?

**Bias related to transformation**

The distance, the astronomical quantity of interest, is the inverse of the parallax measured by the astrometry mission. While the parallax distribution is known to be Gaussian, the distribution function of the distance is not Gaussian. Neither is it symmetric because of the non-linear relation between distance and parallax (see the upper figure to the right). The deformation becomes larger for larger relative parallax errors, $\frac{\sigma_\pi}{\pi_{true}}$ (see the lower figure of the right). The peak of the distribution will move to smaller values with a larger relative error. This means that the distances will be underestimated in the presence of large relative parallax errors.
Why do we need $<\sim 25\mu \text{as}$?

**Bias related to transformation**

The parallax corresponding to a distance of 10kpc from the Sun is $100\mu \text{as}$. The right figure shows that estimated distance is 85% of the true distance due to the bias effect if the relative parallax error is 25%. Disk stars which are in truth at 10kpc may be estimated to be located at only 8.5kpc from the Sun, which puts them barely in the nuclear bulge region. Therefore the error must not exceed $25\mu \text{as}$ ($0.25 \times 100\mu \text{as}$) as a requirement.
★ deviation of stellar centroids due to reflex motions

\[ |\alpha| = \frac{q - l}{(1 + q)(1 + l)} \frac{a}{d} \]

(assumption: \( q \ll 1 \) (\( M_p \ll M_* \)), \( l \ll 1 \) (\( L_p \ll L_* \)) and \( l \ll q \))
In the data analysis of Small-JASMINE, we can use the binary systems whose amount of deviation is much smaller than the target precisions (negligible contribution to the error budget) or the period of the orbit is much larger than the operation time of Small-JASMINE.

The amount depends on the ratio of mass, the ratio of the brightness, angular distance between the two stars which depends on the distance from us, etc. The binary systems may have wide range of values of these parameters.

It is impossible to determine theoretically now whether or not a star has negligible deviation.

The final Gaia catalogue (~2022) will have information of binary systems and so we will distinguish between single and/or single-like stars in the disk in front of the bulge by the use of the Gaia catalogue for the calibrations. Furthermore, if the orbital element of a binary system is resolved by the Gaia data, we can use this binary system for the calibrations after the correction of the binary effect.
A.2.2 Appendix /Fixing the Parallax/ the Number of Stars used for Calibration/ Evidence / Planetary Systems

The amount of deviations of centroids can be given by the same equation described for binary systems. In particular, \( l \ll q \) is a good approximation for the planetary systems, we can use the following approximated equation;

\[
|\alpha| = \frac{M_P \ a}{M_\star d}
\]

\[
= 50[\mu\text{as}]
\left( \frac{M_P}{0.001M_S} \right) \left( \frac{M_\star}{M_S} \right)^{-1} \left( \frac{a}{5\text{au}} \right) \left( \frac{D}{100\text{pc}} \right)^{-1}
\]

Example: Solar-Jupitar system:

\( M_\star = 1M_S \) (Solar mass), \( M_p = M_J \) (Jupiter mass) = 0.001\( M_{\text{SUN}} \),
\( a = 5\text{AU} \) (the orbital period is about 10 years), distance from us \( D = 100\text{pc} \)

\( \rightarrow \alpha = 50\mu\text{as} \)

\* Red giant: if \( M_\star \sim 10M_S \), \( D > 500\text{pc} \) \( \Rightarrow \alpha < 1\mu\text{as} \)

\* Main sequences: if \( M_\star \sim M_S \), \( D > 1\text{kpc} \) \( \Rightarrow \alpha < 5\mu\text{as} \)

Remark: In the reverse situation described just above, we may detect planetary systems and expect scientific outputs.
A.2.3 Appendix / Fixing the Parallax/ the Number of Stars used for Calibration/ Evidence / Hot Spots

* undetected for OBA type stars (detected for Ap)
* only a few cases for single red giants (due to their slow rotations)
* the distribution of occupied ratio of the area of hot spots on the stellar surface

Typically, 20% ~ 40%, up to ~ 60%

![Graph showing occupied area ratio distribution](image)

(Berdyugina 2005, LRSP, 2, 5)
we have possibility that the centroids are moved due to the movement of hot spots for red giants, K, M type stars.

Estimation of the amount of deviations (as large movement as possible)

* size, pattern, period of the rotation, creation-annihilation of hot spots ➔ unknown
we assume the case in which the centroid has as large movement as possible given as follows.

*I_s=0 (the direction of view corresponds to the axis of the rotation)

Ratio of the apparent area of the hot spot $f$, and its position angle $r_{ss}$

Ratio of the deviation of centroid: $\Delta r \equiv f r_{ss} / r^*$

Deviations of the centroid:

$$r^*_\Delta r \sim 0.1 \text{mas} \left( \frac{f}{0.1} \right) \left( \frac{r_{ss} / r^*}{2/3} \right) \left( \frac{R^*}{30 R_\odot} \right) \left( \frac{d}{10^2 \text{pc}} \right)^{-1}$$

$$\sim 0.03 \text{mas} \left( \frac{f}{0.1} \right) \left( \frac{r_{ss} / r^*}{2/3} \right) \left( \frac{R^*}{0.5 R_\odot} \right) \left( \frac{d}{5 \text{pc}} \right)^{-1}$$
Larger $r_{ss}$ => larger deviation, but smaller $f$.
The maximum deviation at around $r_{ss} = \frac{1}{\sqrt{2}}r_*$
Furthermore, we assume that the occupied ratio of the area is 60%.

**Case of red giant**

$$r_* \Delta r \sim 0.1\text{mas} \left( \frac{f}{0.1} \right) \left( \frac{r_{ss}/r_*}{2/3} \right) \left( \frac{R_*}{30 R_\odot} \right) \left( \frac{d}{10^2 \text{pc}} \right)^{-1}$$

$$\sim 0.1\text{mas} \times \left( \frac{0.42}{0.1} \right) \times \left( \frac{1}{2/3} \right) \left( \frac{d}{10^2 \text{pc}} \right)^{-1} \sim 0.45\text{mas} \left( \frac{d}{10^2 \text{pc}} \right)^{-1}$$

Red giant ➔ up to < 7.5μas @d>6kpc, typically <5μas

**Case of MS (K, M type stars)**

$$r_* \Delta r \sim 0.03\text{mas} \left( \frac{f}{0.1} \right) \left( \frac{r_{ss}/r_*}{2/3} \right) \left( \frac{R_*}{0.5 R_\odot} \right) \left( \frac{d}{5 \text{pc}} \right)^{-1}$$

$$\sim 0.03\text{mas} \times \left( \frac{0.42}{0.1} \right) \times \left( \frac{1}{2/3} \right) \left( \frac{d}{5 \text{pc}} \right)^{-1} \sim 134\mu\text{as} \left( \frac{d}{5 \text{pc}} \right)^{-1}$$

MS ➔ up to 6.7μas@d100pc, typically <4.5μas
A.2.4 Appendix /Fixing the Parallax/ the Number of Stars used for Calibration/ Evidence / Gravitational Lens

The centroid of a background star moves with time variation of the brightness of the star because of the general relativistic effect when a compact object passes near the background star on the celestial sphere. In general, we can not predict when and how this gravitational effect will occur. However, we can estimate the possibility of the event.

The optical opacity of the gravitational effect is given as follows:


<table>
<thead>
<tr>
<th>THRESHOLD DIRECTION $\delta_T$ (mas)</th>
<th>Prob. of Observing a Centroid-Shift Variation Larger than $\delta_T$ within $T_{\text{obs}} = 1$ yr for a Given Observed Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulge Stars toward Baade's Window*</td>
<td>$\gamma_{\text{var},0}$</td>
</tr>
<tr>
<td>1..................................</td>
<td>$4.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>5..................................</td>
<td>$8.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>10..................................</td>
<td>$4.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>100..................................</td>
<td>$4.3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Note.—The probability of observing a variation in the centroid shift larger than the threshold $\delta_T$, $\gamma_{\text{var}} \propto \rho_0 T_{\text{obs}} v \delta_T^{-1}$, is shown for sources (1) toward the Galactic bulge, eq. (65), and (2) perpendicular to the Galactic plane, eq. (90), with the reference values $T_{\text{obs}} = 1$ yr, $v = 100$ km s$^{-1}$, and $\rho_0 = 0.08$ $M_\odot$ pc$^{-3}$.

a $\rho(x) = \rho_0$, and $D_S = 8.5$ kpc.
b $\rho(x) = \rho_0 \exp \{-xD_S/H\}$, and $D_S \gg H = 300$ pc.
Threshold of centroid shift $\delta_T \Rightarrow 5\mu\text{as}$ or $1\mu\text{as}$

The expected number of event within 1 year $\Rightarrow$

$5\mu\text{as} \Rightarrow 9 \sim 0.09\%$

$1\mu\text{as} \Rightarrow 43 \sim 0.43\%$

*the deviation of the centroid has the shape of an ellipse.*

The possibility that the period is around one year is very small and the brightness also changes with time.

Hence, we can recognize the gravitational effect by the deviation of the centroid and time variation of the brightness. We therefore have possibility to use the background star for the calibrations after the correction of the gravitational effect.
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE

We first use both Guide Star Catalogue (GSC) and 2MASS Catalogue for estimating the number of stars to be measured by Small-JASMINE.

- We use stars included in **BOTH** GSC and 2MASS Catalogue, having values of B and V, and with error of J, K less than 0.2.
- By using the data, we made a colour-magnitude diagram with V vs. B-V shown right figure.

\[ \text{GSC} \times \text{2MASS} \]

Having B,V error of J,K <0.2

Hw< 12.5mag (limit of SJ)
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE

• We see two groups on the colour magnitude diagram.
• From this diagram, we can separate the main sequence stars and red giants.
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE

- After the identification of the main sequence stars and red giants, we re-plot the colour magnitude diagram in K vs. J-K as shown in right figure.
- Red and blue plots indicate main sequence stars, and red giants, respectively.
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE

Stars with J-K <0.75 are main sequence stars, and stars with 0.75<J-K<2 are red giants.
These stars seen in V, plotted in the region J-K<2, are **disk stars**.
Stars seen in V are not red giants within the bulge.

The argument is as follows.
The brightest M(M5) stars have an absolute magnitude of about **-5.5mag**. If such a star is located at 8kpc distance away from us, it would have an apparent magnitude of **9mag** even if the extinction was zero. If the extinction to the Galactic bulge is assumed to be **Av=15mag**, the apparent magnitude becomes **24mag**. This is fainter than the limiting magnitude of the GSC, **V<18mag**.
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE / Check

Here we check the previous result using absolute magnitude data for each type of star by Wainscoat et al. 1992.

Assumption
• Extinction law
• $A_v=15\text{mag}@8\text{kpc}$
• $A_B/A_v=1.324$
• $A_J/A_v=0.282$
• $A_K/A_v=0.112$
(Rieke & Lebofsky 1985)
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE / Check

Reproduction of the two groups of main sequence stars and giants.

- Colour magnitude diagram in V vs. B-V
- Colour-magnitude diagram in K vs. J-K.

Data: Wainscoat et al
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE

2MASS
Error of J,K <0.2
Hw<12.5mag (limit of SJ)

- We plot the K vs. J-K colour-magnitude diagram again, but now using the complete 2MASS catalogue which also contains stars with no cross match to the GSC and thus no B or V magnitudes.
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE

The additional stars in the region with $J-K>2$ are plotted with green plots. These stars may be bulge stars.
Using the 2MASS data, we plotted stars with J-K<2 on the celestial sphere. As can be seen, the stars are distributed almost homogeneously, representing the disk stars.

On the other hand, stars with J-K>2 are distributed inhomogeneously which means that stars are within the bulge affected by the dust.

Distribution of stars in the sky: (left) J-K<2, (right) J-K>2
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE / Estimation of $G = G(J,K)$

Gaia DR1 $\times$ 2MASS

- error of $J,K < 0.2$mag
- $Hw < 12.5$mag

- 2MASS-Gaia cross matching data that have errors of $J,K$ less than 0.2
- We estimate the fitting function of $G$ as a function of $J$ and $K$.
- $G(J,K) = K + 3.3(J-K)$
A.4 Appendix / Estimation of the Number of Stars with Small-JASMINE / Relation between G and Hw

- G magnitude are obtained from the colour-magnitude diagram in K vs. J-K.
- The number of stars in the region with J-K>2 to be measured by SJ is about 4900 stars.
- The number of stars in the region with J-K<2 to be measured by SJ is about 3500. These stars are brighter than G=16mag.
- Therefore all the disk stars observed by SJ can be measured by Gaia.
- Note that Gaia can observe the stars with the parallax error equal to or less than 20μas only when the stars are brighter than G=16mag.
A.4 Appendix / Estimated Number of Stars

- Estimated number of total stars: 8500
- Estimated number of bulge stars: 4900
- Estimated number of disk stars: 3500

Circular region:
- Total number of stars using Gaia DR1
- More than 3500

Graphs:
- Number of stars observed with SJ
- Estimated number of bulge stars
- Number of stars observed with Gaia
- Estimated number of bulge stars
Example Observing Schedule

- High-latitude survey (HLS: imaging + spectroscopy): 2.01 years
  - 2227 deg² @ ≥3 exposures in all filters (2279 deg² bounding box)
- 6 microlensing seasons (0.98 years, after lunar cutouts)
- SN survey in 0.63 years, field embedded in HLS footprint
- 1 year for the coronagraph, interspersed throughout the mission
- Unallocated time is 1.33 years (includes GO program)
3.7 Satellite System Overview / Orbit

**Dawn-Dusk orbit**

- Sun-synchronous circular orbit
- Altitude = 550km (TBS), inclination = 97.6deg. (TBS)
- LTAN= 6:00/18:00
- Local time of ascending node

**Main target (Galactic bulge) observation** is planned during spring and autumn seasons.

Winter season: The sun is within 45deg from bulge direction.
Summer season: Radiator sees Earth during observation, and detector temperature will be higher than the requirement.

=> Main-target observations will be done in autumn and spring seasons.
3.8 Satellite System Overview / Attitude

Non observation mode
Satellite is rotating around its x axis to avoid looking at Earth

Observation mode
Satellite is rotating around its x axis to look at the Galactic bulge

Satellite attitude near the autumnal equinox
satellite z-axis pointing in the direction of telescope line of sight
satellite x-axis pointing towards Sun (which is perpendicular above the paper)