様式2

SPICA
Mission Requirement Document

本文書は次世代赤外天文衛星 SPICA のミッション要求を規定したものである。
This document defines the mission requirement of SPICA.

キーワード Keyword	次世代赤外天文衛星、SPICA、ミッション要求書
	Next-generation Infrared Astronomy Satellite, SPICA, MRD

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02	2010/06/04					Revised for the consistency with the SRR concept of `nominal' and `optional' instruments.
03	2010/08/04					SRR での指摘事項を受けて、2 章・3 章を改訂した。

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1. はじめに Introduction

1.1. 本書の目的 Purpose of the Document

本文書は、プロジェクトマネジメント実施要領(システムズエンジニアリング推進室長通達 19-1 号 2007 年 4 月 27 日)第 2 章第 6 条に従い、次世代赤外天文衛星 SPICA のミッション要求を規定する。

本文書はユーザである天文コミュニティからの要求をもとに次世代赤外天文衛星 SPICA ミッションの目的を明文化したものである。ミッションの目的は科学的目標と技術的意義として具現化され、それらの目標をもとにミッション要求として規定する。また、ミッション終了後に目標の達成度を評価するための成功基準についても明文化する。図 1.1-1 にミッション要求書の概要図を示す。

本文書で規定したミッション要求は、システム検討のベースラインとなるものである。開発の進捗やシステムの実現、軌道上での運用結果に対し、確実なミッション達成へと進んでいることを確認するための指標とする。また、関連するステークホルダーの意見・期待・ニーズや状況の変化によりミッション要求の見直しが必要となった際には、ミッション要求を変更することに伴うミッション達成への影響について検討するための源泉資料として活用される。

This document defines the mission requirement of SPICA, the next generation infrared space telescope. Based on the motivations and requests from the user, the astronomical communities, this document clarifies the objectives of the SPICA mission. The objectives of the mission are more concretely expressed by various scientific targets (plus also technical purposes), and based on these targets, the mission requirements, such as required specifications of the mission instrumentations, scientific operations etc. are defined. Also the success criteria, by which the evaluation of the mission achievement will be addressed, are clearly described. Overview of structure of this document is shown in Fig.1.1-1.

The mission requirements described here will give the baseline of the study of the system requirements. In the future, this document will also be used to confirm the development status, system performance, and operational results on orbit etc. are well in-line with the mission requirements described in this document. The description in this document may be updated depending on the change in the stake-holder’s opinions or external conditions, and in such case this document will be used as the source and reference document to estimate the effects on the mission achievement.

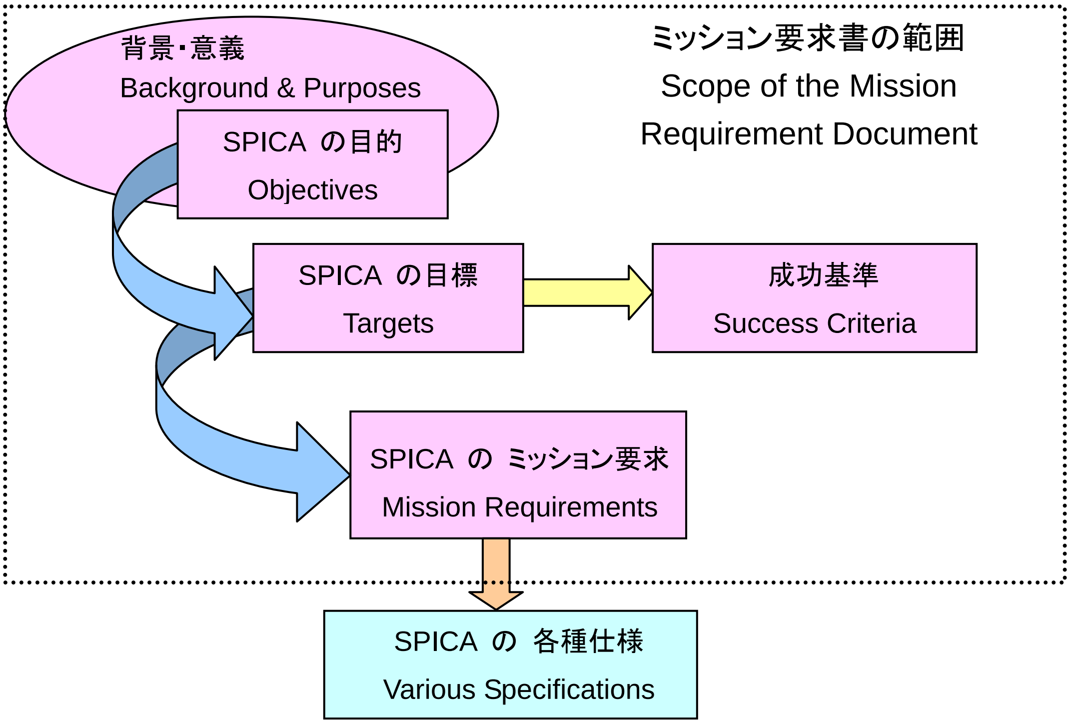


図 1.1-1　ミッション要求書の概要図

Fig,1.1-1 Overview of the structure of Mission Requirement Document

1.2. 関連文書 Related Documents

① 上位文書 Program Documents

1. JAXA 長期ビジョン –JAXA2025- (2005 年 8 月 31 日 第 2 版)
2. 宇宙開発に関する長期的な計画
   (総務大臣・文部科学大臣 2008 年 2 月 22 日)
3. 2010 年代の赤外線天文学
   (光赤外天文将来計画検討会検討報告書編集委員会 2005 年 3 月 20 日)

② 適用文書 Applicable Documents

1. プロジェクトマネジメント実施要領　第 2 章第 6 条
   (システムズエンジニアリング推進室長通達 19-1 号 2007 年 4 月 27 日)
2. SPICA Mission Definition Document
   (Issue　1.0 August 21, 2009)

③ 参考文書 Reference Documents

1. 次世代赤外線天文衛星 SPICA ミッション提案書
   (次世代赤外線天文衛星ワーキンググループ 2007 年 9 月 第 2 版)
2. SPICA A Cosmic Vision Proposal for a Joint JAXA/ESA Mission to Discover Origins of Planets and Galaxies (ESA)
3. 第１９期日本学術会議・天文学研究連絡委員会・特別議事録
4. システムズエンジニアリングの基本的な考え方 初版
   (2007 年 4 月 B 改訂　BDB-06007B)

2. ミッションの目的 Mission Objectives

2.1. 背景および概要 Background and Overview

① 学問的背景 Scientific Background

我々の宇宙は約 137 億年前にビッグバンで生まれた。その後の宇宙の進化の歴史の中で、現在の我々の世界を構成している各種の天体が誕生、進化してきたと考えられている。しかし、それらの天体が「いつ」「どのように」誕生、進化してきのかは、未だによくわかっていない。SPICA は、宇宙の歴史における「天体の誕生と進化」という大きな謎に挑む。

The universe began 13.7 billion years ago by “Big-Bang”, and various kind of objects – constituent of our world – were born and have evolved through the history of the universe. SPICA’s challenge is to resolve the big question：“when” and “how” such objects were born and have evolved.

② 「あかり」との関係 Relation to “AKARI” space infrared telescope

「天体の誕生と進化」という大きな謎を解明するには、宇宙からの赤外線高感度観測が必要不可欠である。様々な天体が形成される時，その温度が絶対温度で 3K から 300K に対応し，赤外線で観測されるからである。宇宙誕生(ビッグバン)の光といわれる宇宙背景放射も，その誕生の際は約 4000K であったが，宇宙膨張のため現在は 3K の温度で観測される。

In order to resolve the “big question”, infrared observation with high sensitivity from space is mandatory, since the temperature of primordial objects is 3-300K emitting majority of their energy in the infrared and submillimeter wavelengths.

宇宙からの赤外線観測を進めるべく、JAXA は 2006 年 2 月に赤外線天文衛星「あかり」を打上げた。「あかり」は全天を観測することを目的の一つとした赤外線サーベイ観測衛星である。従来の赤外線サーベイ観測衛星である IRAS(Infrared Astronomical Satellite・NASA・1983 年打上げ) と比較すると、解像度が画期的に向上しており、「あかり」はいわば究極の赤外線サーベイ観測衛星として成果を挙げ、多くの若い星・原始惑星系円盤や赤外線銀河を発見した。

JAXA launched AKARI infrared astronomy satellite in Feb. 2006. AKARI’s major objective is the advanced all-sky survey in the infrared, with much better spatial resolution than that of IRAS launched by NASA in 1983. AKARI is a suprime infrared surveyor discovered many young, stars, debri disks, and infrared galaxies.

しかしながら「あかり」はサーベイ観測衛星としては優れた空間分解能をもっているものの、高い波長分解能・空間分解能をもとに詳細な観測を行う天文台型の観測衛星と比較すると空間分解能が不足していることは否めない。「あかり」の最も長波長における空間分解能は 50” と人間の視力程度であった。

However, AKARI was not an space observatory. Even though it has excellent spatial resolving power as an all-sky surveyor (50” in the far-infrared), it is not enough to explore the detailed nature of the objects for which a space observatory, which enables us to observe objects with long exposure time and better spectral and spatial resolution, is necessary.

「あかり」のサーベイ観測の結果を活かし、さらなる謎の解明のためには、より優れた空間分解能と感度をもった次世代の天文台型の観測衛星が必要であり、大口径の宇宙望遠鏡が切望されている。

Therefore, the next generation space infrared telescope with a large collecting aperture, superior spatial resolution and the sensitivity, is strongly requested

③ 国際的位置付け Standpoint in the International Trend

「天体の誕生と進化」という大きな謎の解明には、赤外線、特に中間・遠赤外線での高感度の観測を行なうことが必要になる。2010 年代までに計画されている赤外線ミッションは、近赤外線(JWST：James Webb Space Telescope・NASA/ESA・2014 年打上げ予定)やサブミリ波(Herschel：ESA・2009 年 6 月打上げ）に集中したものであり、中間・遠赤外線での高感度観測ミッションは、国際的に見ても SPICA の他に存在していない。

Hershel, aiming to observe mainly submillimeter wavelength beyond 60μm, was launched in June 2009. In this decade only JWST (James Webb Space Telescope, NASA/ESA) is planned to be launched (currently in 2014), which, however, aims to observe mainly near-infrared upto 5μm. Even from the viewpoint in the international trend, only SPICA is aimed to observe mainly mid and far-infrared wavelength with high sensitivity.

ミッション目的・意義 Mission Objectives and Purposes

SPICA は「我々はなぜ、かく在るのか？」という人類の基本的問いの中で特に「銀河誕生のドラマ」および「惑星系のレシピ」を探る次世代赤外線天文衛星である。この宇宙の歴史における「天体の誕生と進化」という大きな謎に挑むため、銀河の誕生と進化、星と惑星系の誕生と進化、物質の進化の研究を行う。中でも、赤外線による観測によって大きな進展が期待される「銀河誕生のドラマ（銀河の誕生と進化過程の解明）」と「惑星系のレシピ（惑星系形成過程の総合理解）」そしてこれらすべての基礎として「銀河星間空間における物質輪廻の解明」を科学的目的として掲げる。これらの相互関係を図 2.1-1 に示す。

Among the basic questions of human beings “who are we? Where are we from?” SPICA will investigate “the drama of galaxy formation” and “the recipe for planetary systems”. In order to challenge this big question in the history of universe, we present three major science objectives: “resolution of birth and evolution of the galaxies”, “thorough understanding of planetary system formation”, and “the transmigration of dust in the universe” as the basis of the former two objectives, with SPICA. In Figure 2.1-1, the relationship of these science objectives is shown.

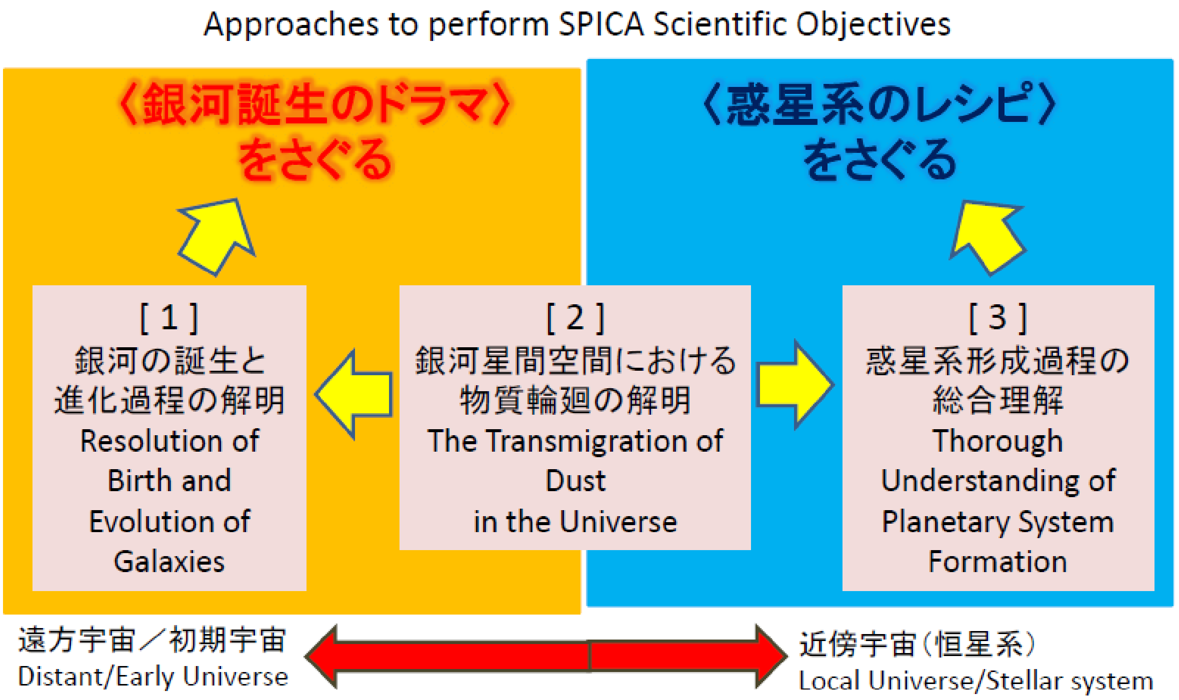


図 2.1-1 SPICA ミッションの３大科学目的相互の関係。

Figure 2.1-1 Relationship among the three major science objectives performed with SPICA.

これらの科学的目的について、特に赤方偏移した宇宙初期の放射と低温物質からの放射に感度の高いスペースからの赤外線の観測によって、大きな科学的進展が期待される。次節から、

具体的に詳しく述べる。

また、科学的意義ばかりでなく、SPICA ミッションには、以下のように重要な技術的意義が存在する：

大型軽量ミラー技術の開拓：「あかり」や Herschel で培われた SiC 冷却軽量鏡技術を発展させ、大口径単一鏡の製作技術・その光学性能の低温での実証技術を開拓する。2009 年に実現された Hershel 宇宙望遠鏡は、遠赤外線〜サブミリ波といった長波長での使用に耐える鏡面精度に過ぎず、しかも温度は 70K であった。

赤外線観測機器技術の開拓：極低温に冷却された望遠鏡によってこれまでになく高感度の赤外線観測を実現するためには、それに見合う高感度・大画素数の赤外線検出器がぜひとも必要である。

効率的冷却システムの開拓：従来の赤外線衛星の概念を打ち破り SPICA は、地上では冷却せずスペースに到達してから望遠鏡・観測装置を冷却する。これを実現するための断熱/放熱技術、機械式冷凍機の独自開発を行い、今後も我が国の資産というべき「効率的冷却システム」の確立を目指す。

ラグランジュ点利用技術の開拓：JAXA 長期ビジョンに掲げる「深宇宙港」という目標の実現の第一歩として、我が国が初めてラグランジュ点を利用した科学観測を実現する意義は大きい。また他のスペースからの天文学ミッションにおいても L2 点は非常に魅力的である。

Besides the scientific objectives, there are also important mission objectives on the technology in space mission:

Light-weight, large mirror technology for space mission: based on the heritage of SiC low-temperature, light-weight mirror technology for AKARI and Hershel, we will undertake the establishment of fabrication and low-temperature performance evaluation for large, monolithic, light-weight mirror. The large-mirror onboard Hershel achieved surface accuracy which is only capable to use at far-infrared and submillimeter wavelengths and the mirror is 70K.

Development of advanced instrumentation for space infrared observations: to achieve the extremely high sensitivity with cooled telescope, large-format infrared array detectors with high-sensitivity are mandatory.

Effective cooling technology in space: unlike the past infrared telescopes in space, the telescope and the instruments of SPICA will be cooled when the spacecraft will be put into space.

Technology Application at Sun-Earth Lagrangian point: as the first step toward the “deep-space port”, one of the targets in the JAXA’s long-term Vision, scientific observations with SPICA in L2 point will be the 1st space technology application among the Japanese space activities. The L2 point is also very promising place for other space astronomy missions.

SPICA の科学的目的を表 2 にまとめる。「目的」はミッションの内容に重点を置いた記述としている。そのため「目標」に比べて抽象的であり、長期的視点に立った記述である。

In Table 2, scientifc objectives of SPICA are summarized. “Objectives” are described somewhat abstractly than “Targets”, since they express more emphasis on the purpose of the mission in the long-term vision in science and space technologies.

「ミッション目標」について Targets of the Mission

「目標」は「目的」をもとに具体化された、目指す成果・数値・数量・時間などに重点を置いた記述としている。そのため、目的を達成するための観測方法やそれによって得られる成果について記述している。

SPICA’s targets are shown in Table 2. “Targets” are concrete description of aimed results, quantitative numbers, or observing duration, etc., based on the “Objectives”. Thus observing methods as well as expected results are also described.

SPICA ミッションの目標（科学および技術）を以下にまとめる：

科学的目標

- 銀河誕生のドラマを探る

宇宙の進化の歴史を示す宇宙赤外線背景放射が、どのような天体から構成されているかを明らかにする。

宇宙の歴史の大半(宇宙年齢の 90%以上）の期間における、銀河・星形成史を明らかにする。

- 物質輪廻の解明

銀河星間空間における物質循環、特にダストの形成と進化過程を明らかにする。

- 惑星系のレシピを探る

惑星系の形成過程を総合的に明らかにする。

太陽系内における小天体・固体物質分布の観測から、太陽系形成の歴史を探る。

技術的目標

- 日本の戦略宇宙技術の開拓

我が国で初めてラグランジュ点の利用技術を確立する

今までの冷却システムに比べて、重量効率をはるかに向上させた冷却システムを実証する。

また SPICA を用いて研究活動を推進する天文科学コミュニティが掲げる科学的目標を表 2 に示した。この１６項目（上記の衛星ミッション目標も含まれている）には、現時点でのオプション機器・機能が使用されるもの含まれている。システム定義審査までには、コスト及び技術的実現性と科学的価値のトレードオフ検討を進め、その結果、搭載することに決定した装置及び機能のみを使用する前提で再整理する。その上で、これらすべてを達成することを目指して、観測運用計画を立案する。

「成功基準(サクセスクライテリア)」について Success Criteria

「成功基準」は「目標」の達成度の度合を判断するための評価基準である。「成功基準」は、JAXA が国民に対して宣言するものであり、JAXA における経営審査を経て宇宙開発委員会における推進部会にて審査されるものである。(NC 版時点では、宇宙開発委員会における審査未了)

なお、成功基準は達成度を明確に判断できるよう簡潔な表現としているため、目標とセットで確認する必要がある。

The “Success Criteria”, also presented in Table 2, are criteria for evaluating the achievement of the “Targets” of the mission. The “success criteria” are also a JAXA’s declaration to the people in Japan: they are reviewed at the JAXA headquarter first and then reviewed by the Space Advisory Committee of the Japanese government. Note that the success criteria are just written concisely in order to judge the mission achievement clearly: thus the corresponding targets should be simultaneously referred.

「フルサクセス」はプロジェクトが各種リソースや制約を考慮した上で達成すべき事項を記述している。SPICA では、キーサイエンスとして独創的かつ先端的な成功を達成するための基準を定めている。成果の規模としては【中】以上のサイエンスとして定義する。

“Full success” level should be achieved by the project within the available resources and constraints. In SPICA project, this is the standard for the successful achievement of unique and advanced key sciences. The size of results is defined as [moderate] impact on the corresponding scientific topics.

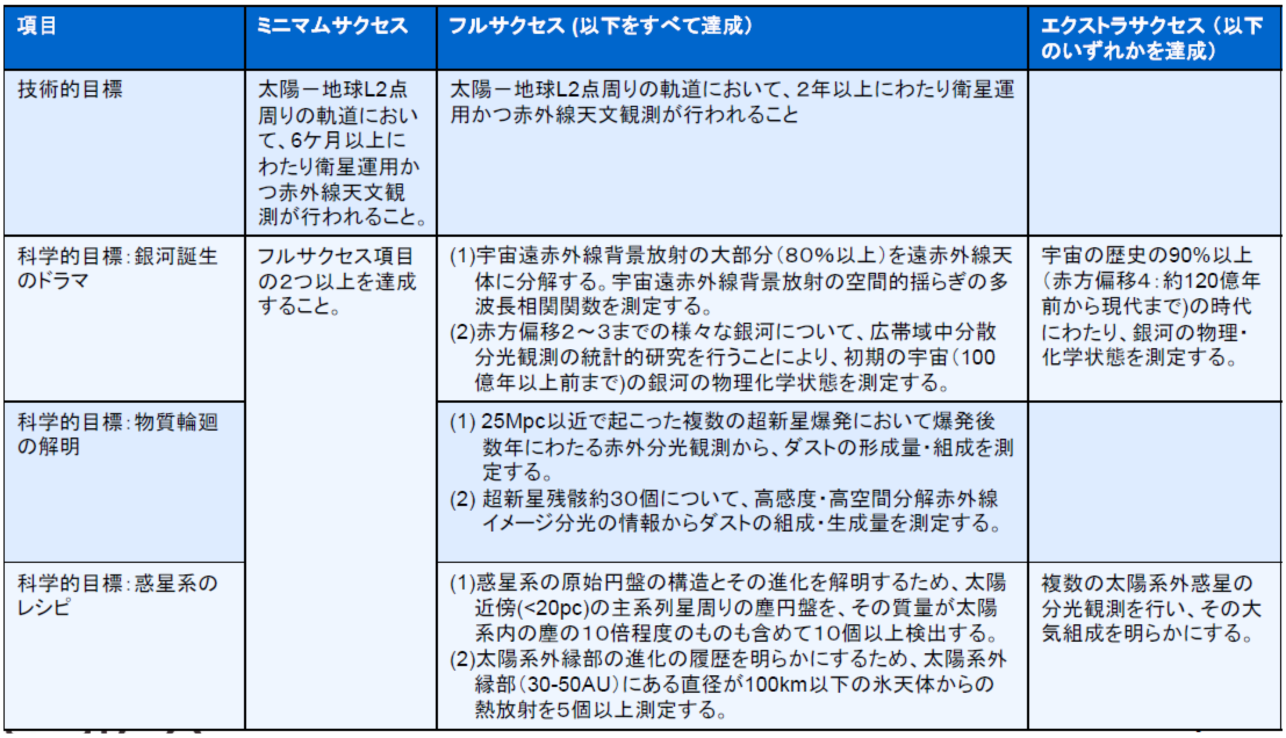
「エクストラサクセス」はパラダイムを変えるような大きな成果を達成するための基準を定めている。成果の規模としては【大】のサイエンスと定義する。なお、設計寿命を超えた観測により得られる成果あるいは不定性などの運・不運に左右される事項については、それらの条件を記述する。

“Extra Success” is a criterion to judge if the results of the mission is huge impact, even changing the paradigm. The size of results is defined as [large] impact on the corresponding science. In addition, if the results are obtained from observations beyond the designed mission life, the condition of them shall be defined.

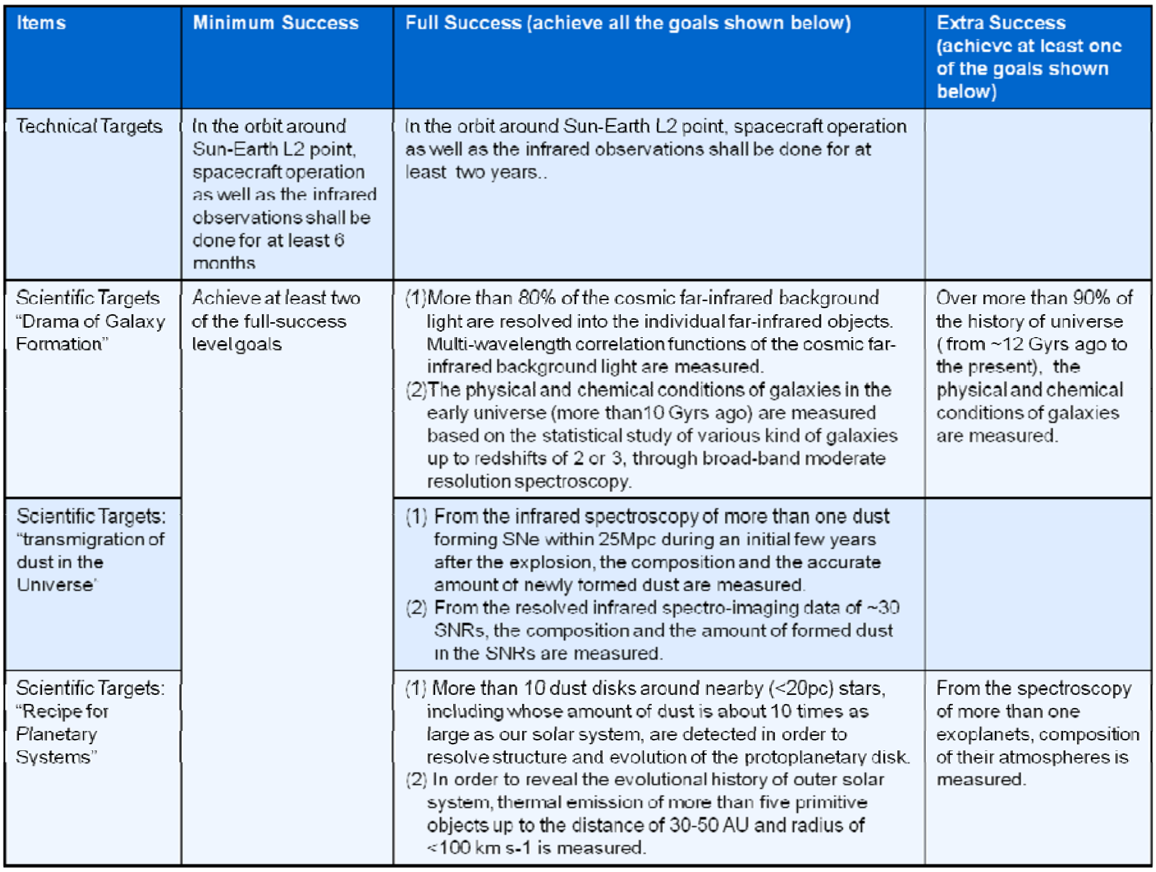
「ミニマムサクセス」は投じた費用に対する最低限の科学的成果が得られる基準を示す。SPICA では、前節に掲げたフルサクセス成功基準のうち 2 つ以上達成することとする。

“Minimum Success” is a criterion to judge if the mission achieved the minimum scientific goals in exchange for the paid cost. In case of SPICA, among the above criteria, “Minimum Success” is defined to achieve at least two [moderate] impact scientific goals.

表 2.1-2 に SPICA ミッションの成功基準をまとめる。



項目	ミニマムサクセス	フルサクセス (以下をすべて達成)	エクストラサクセス（以下のいずれかを達成）
技術的目標	太陽ー地球L2点周りの軌道において、6ケ月以上にわたり衛星運用かつ赤外線天文観測が行われること。	太陽ー地球L2点周りの軌道において、2年以上にわたり衛星運用かつ赤外線天文観測が行われること	
科学的目標：銀河誕生のドラマ	フルサクセス項目の2つ以上を達成すること。	(1)宇宙遠赤外線背景放射の大部分（80%以上）を遠赤外線天体に分解する。宇宙遠赤外線背景放射の空間的揺らぎの多波長相関関数を測定する。 (2)赤方偏移2～3までの様々な銀河について、広帯域中分散分光観測の統計的研究を行うことにより、初期の宇宙（100億年以上前まで)の銀河の物理化学状態を測定する。	宇宙の歴史の90%以上（赤方偏移4：約120億年前から現代まで)の時代にわたり、銀河の物理・化学状態を測定する。
科学的目標：物質輪廻の解明		(1) 25Mpc以近で起こった複数の超新星爆発において爆発後数年にわたる赤外分光観測から、ダストの形成量・組成を測定する。 (2) 超新星残骸約30個について、高感度・高空間分解赤外線イメージ分光の情報からダストの組成・生成量を測定する。	
科学的目標：惑星系のレシピ		(1)惑星系の原始円盤の構造とその進化を解明するため、太陽近傍(<20pc)の主系列星周りの塵円盤を、その質量が太陽系内の塵の10倍程度のものも含めて10個以上検出する。 (2)太陽系外縁部の進化の履歴を明らかにするため、太陽系外縁部（30-50AU）にある直径が100km以下の氷天体からの熱放射を5個以上測定する。	複数の太陽系外惑星の分光観測を行い、その大気組成を明らかにする。



Items	Minimum Success	Full Success (achieve all the goals shown below)	Extra Success (achieve at least one of the goals shown below)
Technical Targets	In the orbit around Sun-Earth L2 point, spacecraft operation as well as the infrared observations shall be done for at least 6 months	In the orbit around Sun-Earth L2 point, spacecraft operation as well as the infrared observations shall be done for at least two years..	
Scientific Targets “Drama of Galaxy Formation”	Achieve at least two of the full-success level goals	(1)More than 80% of the cosmic far-infrared background light are resolved into the individual far-infrared objects. Multi-wavelength correlation functions of the cosmic far-infrared background light are measured. (2)The physical and chemical conditions of galaxies in the early universe (more than10 Gyrs ago) are measured based on the statistical study of various kind of galaxies up to redshifts of 2 or 3, through broad-band moderate resolution spectroscopy.	Over more than 90% of the history of universe (from ~12 Gyrs ago to the present), the physical and chemical conditions of galaxies are measured.
Scientific Targets: “transmigration of dust in the Universe”		(1) From the infrared spectroscopy of more than one dust forming SNe within 25Mpc during an initial few years after the explosion, the composition and the accurate amount of newly formed dust are measured. (2) From the resolved infrared spectro-imaging data of ~30 SNRs, the composition and the amount of formed dust in the SNRs are measured.	
Scientific Targets: “Recipe for Planetary Systems”		(1) More than 10 dust disks around nearby (<20pc) stars, including whose amount of dust is about 10 times as large as our solar system, are detected in order to resolve structure and evolution of the protoplanetary disk. (2) In order to reveal the evolutional history of outer solar system, thermal emission of more than five primitive objects up to the distance of 30-50 AU and radius of <100 km s-1 is measured.	From the spectroscopy of more than one exoplanets, composition of their atmospheres is measured.

表 2.1-2 SPICA ミッションの成功基準

Table 2.1-2 Success Criteria of SPICA mission

また、SPICA を用いて研究活動を行う天文科学コミュニティが掲げるフルサクセス・エクストラサクセス成功基準も表 2 に示した。これらは科学目標同様、現時点でオプションの装置・機能を使用するものを含んでおり、システム定義審査までに搭載することに決定した装置及び機能のみを使用する前提で再整理する。

搭載する科学観測装置について Focal-Plane scientific instruments onboard

焦点面観測装置として以下を想定する（実際の搭載に向けたプロセスについては別文書に記載される）：

中間赤外線撮像装置(MIRACLE)
中間赤外線中分散分光装置(MIRMES)
中間赤外線高分散分光装置(MIRHES)
遠赤外線分光撮像装置(SAFARI)
焦点面ガイドカメラ(FPC-G)
近赤外線カメラ(FPC-S)
中間赤外線コロナグラフ(SCI)
遠赤外サブミリ波分光装置(米国主導装置：BLISS 等。以下 BLISS で代表する)

このうち、MIRACLE の短波長（5-20μm）低分散分光機能、MIRMES の短波長（10-20μm）中分散分光機能、MIRHES、FPC-S、SCI、米国主導装置はオプションである。ただし FPC-S は FPC-G のバックアップ機能を有する必要があり、オプションとするのは科学観測機能のみについでである。

これらのより詳しい仕様については、Mission Definition Document (MDD) [AD-2]に記載されている。

Currently considered Focal Plane-instruments (FPIs) onboard SPICA are as follows:

MIRACLE (Mid-InfRAred Camera w/o Lens)
MIRMES (Mid-IR medium-resolution echelle spectrometer)
MIRHES (Mid-IR high-resolution echelle spectrometer)
SCI (SPICA Coronagraph Instrument)
SAFARI (SPICA Far-infrared Instrument)
Far-IR & Submillimeter spectrometer (US-lead instrument, such as BLISS : Background-Limited Infrared-Submillimeter Spectrograph)
FPC (Focal-plane finding camera) #FPC-G is a guider camera for the attitude control.

For their detailed specifications, see Mission Definition Document (MDD) [AD-2].

2.2 Resolution of Birth and Evolution of Galaxies

Objective #1: Probing the High-Redshift Universe toward the Epoch of Reionization

We will identify and characterize dust-obscured (i.e., IR-luminous) galaxies at 4<z<10, a redshift range hitherto unexplored by far-IR/submm observations, and investigate whether such a population of galaxies played an important role in the early Universe.

Observational cosmology is now on the verge of making another great breakthrough in the history of science: to identify the first generation of galaxies that appeared and reionized the intergalactic space, thereby ending the so-called "Dark Ages" of the Universe. This process, called "cosmic reionization", marks a major phase transition of the Universe, after which the intergalactic space has become transparent to HI ionizing radiation. Recent WMAP observations indicate that cosmic reionization took place around z~10 (e.g., Dunkley et al. 2009) while QSO absorption-line studies suggest that the reionization process is not complete to z~6 (e.g., Fan et al. 2006). Thus, a fundamental question is "When and How the Universe experienced the re-ionization epoch ? Did the first dust already emerge during the re-ionization era and absorb ionizing photons?" Our challenge, therefore, is to understand how galaxies formed and evolved during this critical epoch in the history of the Universe.

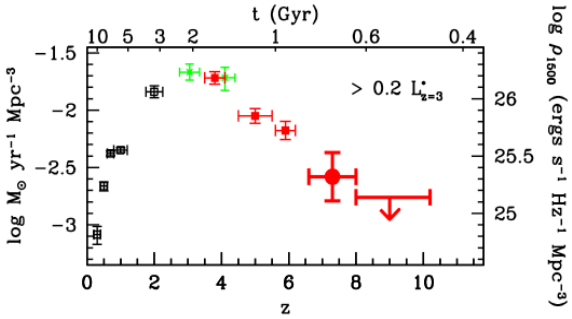


Fig.2.2-1: Evolution of the UV luminosity density (right axis) and the corresponding UV-derived star formation rate density (left axis) integrated down to 0.2 $L^*_{z=3}$ in each redshift bin (Bouwens et al. 2008).

Deep optical and near-/mid-infrared observations are now routinely detecting galaxies up to a redshift of 7 (and even beyond photometrically), providing a first glimpse of galaxy populations near the epoch of reionization. Preliminary results suggest that the rest-frame UV luminosity density (and therefore the UV-derived star formation rate density (SFRD)) is sharply declining from z~3-4 to z~10 (Bouwens et al. 2008; Fig.2.2-1). The next question is whether this observed sharp decline reflects the true history of cosmic star formation or it is substantially steepened by the effect of dust extinction. For example, when z~3-4 Lyman Break Galaxies (LBGs) were first studied, a similar decline was seen at z~3-4, but it was later understood as the effect of dust extinction. In fact, when corrected for dust extinction, the UV-derived SFRD stays nearly flat at z~1-4 (e.g., Steidel et al. 1999). Furthermore, even heavier dust extinction could make galaxies drop out of optical (i.e., rest-frame UV) surveys all together (e.g., LBG surveys), and indeed such a population of luminous but heavily dust-obscured galaxies have been discovered by submillimeter observations (e.g., Smail et al. 2002). This leads to a question we hope to answer with SPICA: "Did dust-obscured (i.e., IR-luminous) galaxies play an important role in the early history of the Universe at 4<z<10?" Such a population could certainly hide a substantial amount of star-forming activities at z>4 from optical/near-IR observations although its relevance to cosmic reionization would need to be examined due to the difficulty of dust-obscured galaxies to release intergalactic HI ionizing radiation efficiently. However, the dust emission as a high-z probe provides us with unique opportunity to identify the major epoch of heavy element production.

SPICA will play a major role in investigating high-z sources (1) to identify $4<z<10$ IR-luminous galaxies and high-z quasars, and (2) to characterize individual detected sources. For (2), we expect a number of interesting targets to be known beforehand from various JWST/ALMA deep surveys as well as from the SPICA surveys mentioned below. We will also mention the great potential offered by lensing cluster surveys (3).

(1) Identify $4<z<10$ IR-luminous galaxies

SAFARI Spectro-imaging survey of 7.7 μm PAH emitters: The 7.7 μm PAH feature is the most luminous and conspicuous emission feature seen in the rest-frame mid-IR spectra of star-forming galaxies. For example, the 7.7 μm PAH features of z~2 star-forming submillimeter galaxies (SMGs) have luminosities of $\sim 10^{10}\ L_{\odot}$ (Pope et al. 2008; Fig.2.2-2). With a flux sensitivity of 10^{-19} Wm^{-2} in the low-resolution (R~20) FTS mode, SAFARI can conduct an efficient survey of such strong 7.7 μm PAH emitters up to z~10.

MIRACLE Narrow-band imaging/multi-slit survey of Hα emitters: Hα is the brightest hydrogen recombination line, and therefore will serve as a good marker for high-redshift galaxies. Hα will be redshifted into the MIRACLE passband at z~7 (5.25 μm). With specifically designed narrow-band filters/slitmaks together with the large FOV, MIRACLE can conduct an efficient survey of Hα emitters at $z>7$. Note that such a Hα survey will detect not only dusty IR-luminous galaxies but also UV-bright galaxies with minimal dust extinction and strong line-emitters such as giant Lyα blobs.

MIRACLE and FPC-S spectroscopy of high-z quasars: through future NIR imaging surveys from the ground or from the space, it is expected that many quasars will be discovered at $z > 6$ by the launch of SPICA. One of the important issues of high redshift quasars study is how rapidly quasars are growing at high redshift, as many different models are proposed to explain the existence of $\sim 10^{9}$ $M_{\odot}$ black holes at $z \sim 6$ when the universe was less than 1 Gyr old. AKARI NIR grism spectroscopy has provided a glimpse of the supermassive black hole (SMBH) growth at $z \sim 6$, showing that the luminous quasars are shining near at the Eddington luminosity, unlike the lower redshift counterparts. The AKARI result suggests that SMBHs seem to be in rigorous growth phase at $z > 6$ with the SMBHs with 10^{10} $M_{\odot}$ appearing only at $z < 6$ (Im et al. 2010 in preparation; Im 2009 at AKARI conference). SPICA's MIR and FIR coverage will detect the IR fluxes of high redshift quasars, allowing us to estimate the Eddington ratio – a crucial piece of information for estimating the accretion rate – of high redshift quasars. The MIRACLE spectroscopy, together with FPC-S's LVF spectroscopy, will provide us with the Balmer line measured BH masses as well as metal line information in the optical wavelengths which are important to trace the metal enrichment history of the broad line region around SMBH in the early universe. A 5-year blind parallel imaging survey in NIR with three broadband filters to ~26-27 AB magnitude limit has a potential to uncover dozens of quasars at $z > 6$ over more than 50 square degree area which will be difficult to find from the ground-based surveys or even with JWST.

(2) Characterize individual detected sources

BLISS Fine-structure/H_2 line spectroscopy: Some low-redshift (z~0.2) luminous galaxies (e.g., brightest cluster galaxies in strongly cooling cluster cores) show very strong fine-structure (e.g., [Ne II] 12.8 μm) and H_2 lines with luminosities up to ~10^9 $L_\odot$ (Egami et al. 2006; Fig.2.2-2). With a flux sensitivity of 10^{-20} Wm^{-2} in the medium-resolution (R~700) mode, SPICA/BLISS can detect such strong lines up to z~10, providing information on the physical properties of ionized gas components as well as of H_2-emitting regions. Compared to these narrow emission lines, the broad PAH features will be much easier to detect, and the strength of the 7.7 μm PAH feature, for example, may be used to estimate the metallicity.

MIRACLE rest-frame optical spectroscopy: MIRACLE should perform rest-frame optical spectroscopy of high-redshift galaxies in order to diagnose their nature by using the line ratio, although JWST has a similar capability.

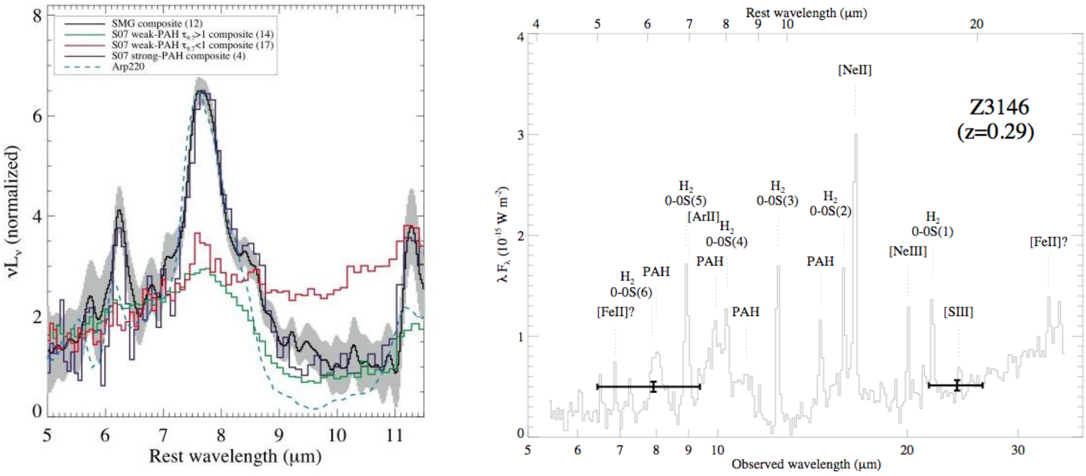


Fig.2.2-2: (Left) Strong 7.7 μm PAH feature detected in z~2 SMGs (Pope et al. 2008); (Right) Strong [Ne II] 12.8 μm fine-structure line as well as abnormally luminous H_2 lines detected in the brightest cluster galaxy in Zwicky 3146, an X-ray-luminous galaxy cluster in which the existence of a cluster cooling flow is suspected (Egami et al. 2006).

FPC-S follow-up of GRBs: Gamma-ray bursts (GRBs) are the most energetic events in the universe. Their extreme brightness makes it possible to detect them at very high redshift, and GRB afterglow has been identified out to z=8.3 (Tanvir et al. 2009; Im et al. 2009), which marks the highest, spectroscopically confirmed redshift of any astronomical object. Their extreme brightness in the initial phase allows us to use them as a probe of the intergalactic medium at the epoch of re-ionization. We expect current and future GRB missions continue to provide prompt alert and localization of GRBs which are candidates for being at the highest redshifts ($6 < z < 15$). Although these GRBs at the reionization epoch will be studied with JWST, a rapid target of opportunity observations with FPC-S, especially with LVF low resolution spectroscopy mode, will enable us to identify the exact location of the redshifted Lyman break and going deep to identify trace of a small fraction of ionized Hydrogen in IGM. Subsequent follow-up observation with MIRACLE or SAFARI will provide an exciting opportunity to understand the GRB infrared emission which is poorly understood. The GRBs will be the brightest sources at the reionization epoch, therefore rapid GRB follow-up observations through SPICA will provide a unique opportunity to examine the high redshift universe. To make this observation possible, FPC-S and another science instrument should be operated in parallel so that one can execute a rapid switching from one instrument to another.

(3) Lensing cluster surveys

By observing the fields of massive lensing clusters and thereby taking advantage of their great gravitational lensing power, we can increase the sensitivities by up to a factor of 20-30.

This great gain in sensitivity is especially important if we consider the possibility that higher-redshift galaxies may be systematically less massive (and therefore less luminous) as predicted by hierarchical structure formation theories. Note that both SAFARI and MIRACLE have FOVs that are large enough to contain the strongly lensed cluster-core region (radius~1').

SPICA's power: Despite its greatly improved far-IR/submm sensitivities, Herschel is unlikely to be able to probe the Universe at z>3-4 because of its confusion limit. Having the same telescope size, SPICA is also bounded by the same limit, but its excellent spectroscopic capabilities (e.g., SAFARI, BLISS) will make it possible to detect sources deeper into the confusion by exploiting spectroscopic information. In fact, such spectroscopic capabilities are essential for SPICA to penetrate the confusion limit and fully utilize the excellent sensitivities afforded by the cold telescope.

ALMA, together with JWST, is likely to detect and identify dust-obscured (i.e., IR-luminous) galaxies well beyond a redshift of 4 and toward z~10. However, the rest-frame mid-IR spectral range, which only SPICA can probe, will be crucial to understand the properties of detected sources (e.g., AGN vs. Star formation through the PAH feature strength). Also, SPICA will offer significantly faster mapping capabilities with respect to ALMA and JWST, and this may become an important factor when we search for rare high-redshift galaxies.

Objective #2: Origin of Cosmic IR Background

We will resolve the cosmic far-infrared background light into individual objects, and reveal the origin of the cosmic far-infrared background residual brightness and fluctuations.

Since the Cosmic Infrared Background (CIB) has been found with the COBE satellite (Puget et al. 1996; Hauser et al. 1998), it has been known that a large fraction of the radiation energy in the Universe is released in the far-infrared wavelength. Main source of the far-infrared background has been thought to be the re-emissions of UV light absorbed by dust in the star-forming galaxies at high redshifts. Up to now, many efforts have been made to resolve the CIB into individual galaxies by deep surveys with infrared space telescope such as ISO, Spitzer and AKARI. However, only 10-30% of the CIB can resolve to each galaxies, and main bulk of the CIB is still unknown well.

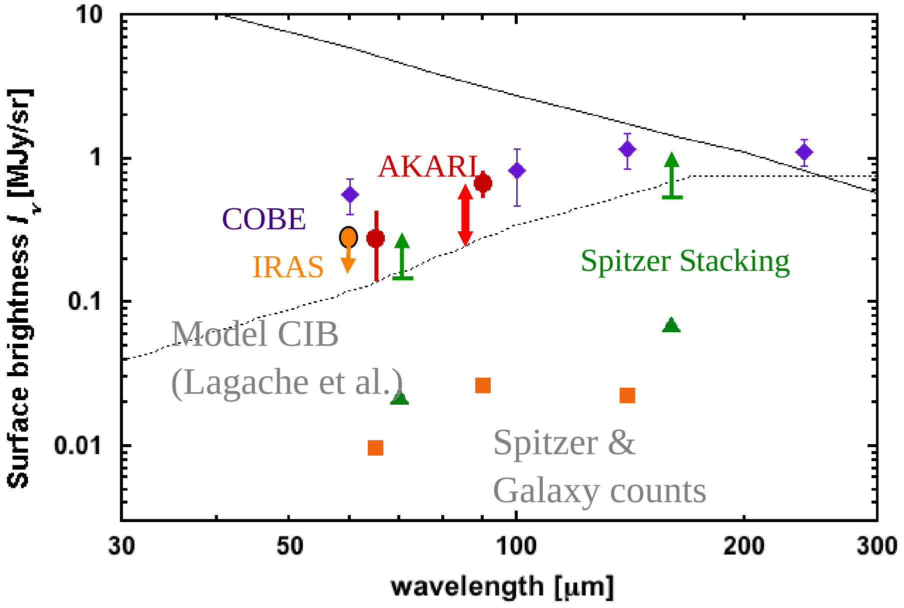


Fig.2.2-3 The absolute brightness of the CIB measured by AKARI, compared with the integrated flux of resolving galaxies.

By using the ultimate sensitivity and high resolution of SPICA, we will be able to resolve the CIB into individual objects, and reveal the origin of the cosmic far-infrared background brightness and fluctuations. The scientific objectives of this program are as follows.

1). Source counts for infrared galaxies

Because SPICA has a large 3-m class cold(<6K) telescope, its sensitivity is at least 2 orders of magnitude better than that of Herschel, and its spectral resolution is at least 3 times greater than that of AKARI and Spitzer. With an ideal sensitivity for point sources, SPICA has a capability to resolve 90% and 60% of the CIB at 70μm and 160μm, respectively (Dole et al. 2004). Galaxy number counts are useful to constrain the evolutionary scenario of galaxies. AKARI results indicate the necessity of the multi-band galaxy number counts, especially around the 100μm (Shirahata et al. 2009). Furthermore, with low-resolution spectro-imaging capability of SAFARI, we may able to resolve sources below the turn-over flux density (~1mJy at 70μm) and obtain their low-resolution SEDs at 35-210μm from which we can infer their crude redshifts.

2). Examination of the properties of detected individual galaxies

In order to reveal what kinds of galaxy are dominant in the CIB, the measurements of SEDs of detected sources are very important. AKARI extra-galactic deep survey discovered the very young pure-starburst ULIRGs (Takagi et al. 2009) and the extremely red objects which have the evidence of co-evolution of both the obscured AGN and starburst (Matsuhara et al. 2009). We can detect statistically significant number of these galaxies beyond z~3 with SAFARI and MIRACLE multi-band imaging. Moreover, we have a possibility to detect the dust-obscured (i.e., IR-luminous) galaxies at 4<z<10, which are the key objects to probe the high-redshift universe toward the epoch of reionization.

3). Stacking analysis with mid-infrared and sub-mm wavelength

The stacking analysis with other wavelength is a useful method to investigate the properties of unresolved sources. Because the galaxy confusion limit at the mid-infrared wavelength is much lower than that at far-infrared wavelength, the stacking analysis for the mid-infrared wavelength have enough possibility to escape from the galaxy confusion limit. On the other hand, because the cosmic sub-mm background are almost completely explained by distant sub-mm galaxies, the stacking analysis for the sub-mm galaxies can prove the distant universe.

4). Absolute brightness and spatial fluctuations of CIB

As the results of AKAFI far-infrared deep survey, we obtained new limits on the absolute brightness of CIB, and found the signature of the galaxy clustering at angular scales of 10-30 arcmin (Matsuura et al. 2009). With the aim to detect the sign from the 1st stars at the re-ionization epoch of the universe, we will study the far-infrared background fluctuations in an effort to reveal their origin through detailed analyses such as SED fitting to multi-wavelength images.

We propose a multi-wavelength far-infrared deep survey with making use of the very unique capability of the SAFARI on SPICA, to obtain statistically significant number of source samples and to detect clearly the CIB fluctuation with the angular distance up to degree-scale. In order to measure the SEDs of detected galaxies and the absolute brightness of CIB, low-resolution spectro-photometric imaging mode ($\Delta\sigma$~10 cm^{-1}) will be very useful. The required detection limit is ~300μJy (5-σ). To avoid the galactic cirrus contamination, a low HI-column density region should be selected for the survey area. The follow-up observations with MIRACLE imaging with band filters are also necessary.

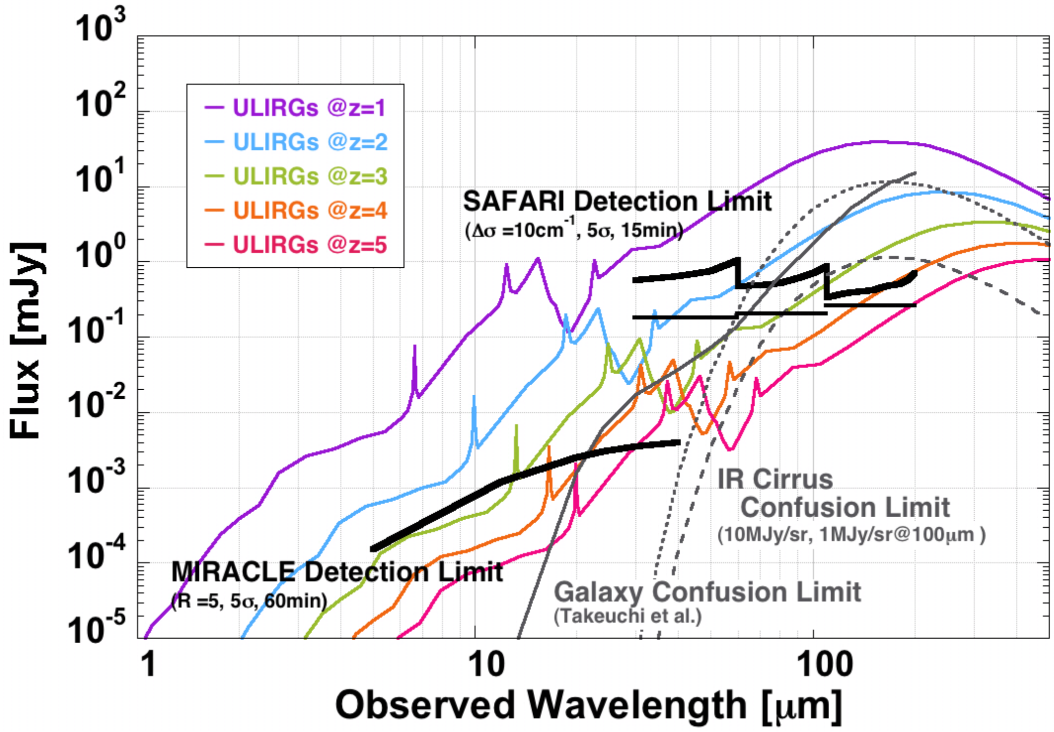


Fig.2.2-4a Predicted performance of SAFARI and MIRACLE with SED template of ULIRG at various redshifts.

In order to measure the absolute brightness of the CIB, we should cool not only the telescope but also the baffle, as possible as we can. We also need the cold shutter and the calibration lamps.

5) Near-IR CIB observation with FPC-S

Light of first stars could be observed as background radiation in the near-IR. COBE/DIRBE and IRTS/NIRS have tried to detect this and an excess emission background was detected.

AKARI recently observed fluctuation of the sky towards NEP and clearly detected a large scale structure (Fig.2.2-4b). The fluctuating component at large angles has a blue stellar spectrum, which cannot be explained by the clustering of faint galaxies. A typical angular scale of the structure, 200 arcsec, corresponds to ~10 Mpc at present, that is a typical distance between cluster of galaxies. These results could be a piece of evidence on the structure formation at pop.III era.

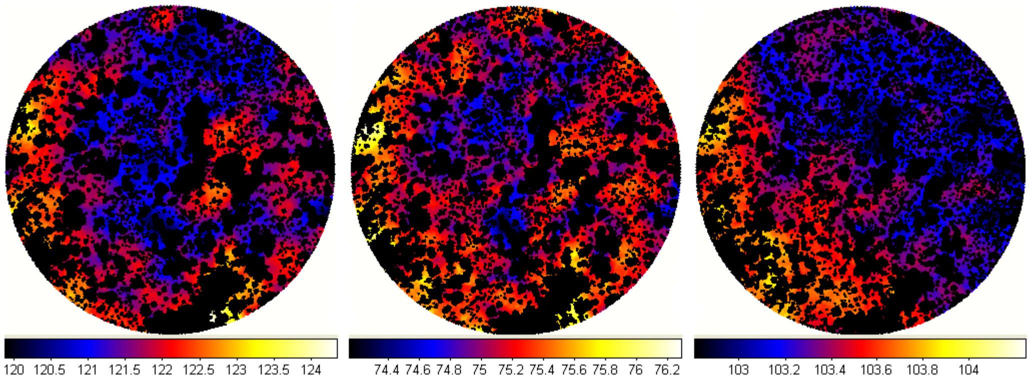


Fig.2.2-9 Smoothed image of NEP field observed with AKARI. Angular diameter is 10 arc-minutes. Wavelength band is 2.4, 3.2 and 4.1 μm, from left to right.

FPC has a unique capability of surface spectroscopy at 0.8 ~ 5 μm with a combination of linear variable filter and step scan of the sky. Measurement of the spectrum of the sky with low spectral resolution certainly provides important data to investigate pop.III era. Larger field of view and much bigger throughput of FPC/SPICA than those of JWST makes it possible to achieve unique observations on CIB.

a) Spectrum of cosmic near-infrared background

FPC is powerful to measure the spectrum of the sky. Observations at several points on the sky makes it possible to obtain the model and template of the spectrum of zodiacal light. By subtracting zodiacal light and diffuse galactic light, spectrum of excess emission will be obtained even at the shorter wavelength side. Thanks to high sensitivity of FPC/SPICA, removal of foreground sources, faint stars and galaxies, can be executed much better than previous observations. If excess emission is due to pop.III stars, spectral peak at around ~1 μm should appear. In this case, the peak indicates the redshifted Lymann a at the end of pop.III star formation. Peak position and spectral shape provide important clue to study the star formation history of pop.III era.

b) Fluctuation measurement

Measurement of fluctuation of sky also provides important result. Compared with AKARI and Spitzer, detection limit and angular resolution are much better, and which faint sources down to ~27 mag. can be removed. This makes it possible to detect fluctuating power at ~10 arcsec, since shot noise due to faint galaxies is much lower than AKARI and Spitzer. Furthermore, the fluctuation map can be obtained for the wide wavelength range from 0.8 ~ 5 μm. Absolute fluctuating power and angular dependence of fluctuation, and their dependence of the wavelength are crucial pieces of evidence to study the structure evolution at pop.III era.

Objective #3: Metallicity Evolution of Evolving Galaxies Revealed with SPICA

We will explore the metallicity of high-z dusty galaxies, which are in the evolving phase in the galaxy evolutionary processes. We will use FIR emission lines that enable us to study the metallicity in dust-enshrouded parts in galaxies.

The unprecedented spectroscopic sensitivity of SPICA in mid and far-infrared will enable us to substantially improve our understanding of the dust-obscured star-formation and AGN growth in galaxies. This is because in the mid- and far-infrared regions there are plenty of diagnostic lines to trace the star formation and the gas accretion to the super-massive black holes. The diagnostics lines are atomic/ionic fine structure lines (Spinoglio, Malkan 1992), molecular lines such as H_2, UV-excited emission bands of Polycyclic Aromatic Hydrocarbon molecules (PAHs), and the silicate features. The spectrometer onboard Herschel can detect the brightest objects at z~1, while SPICA will be able to carry out spectroscopic surveys out to z~3. Here we focus on the metallicity measurement of dusty galaxies, one of unique capabilities of SPICA, in the following.

Measuring the metallicity of galaxies at various redshifts is a powerful way to give constraints on the galaxy evolutionary scenarios, since the chemical properties of galaxies are the result of their past cumlative star-formation. Especially the tight mass-metallicity relation of galaxies (i.e., more massive galaxies have higher metallicity; hereafter MZR) is important, because the MZR suggests more efficient loss of created metals thgough galactic superwind phenomena in less-massive galaxies (e.g., Tremonti et al. 2004). A more interesting issue is the redshift evolution of the MZR. Maiolino et al. (2008) reported a mass-dependent evolution of the MZR between $0<z<3$; i.e., less-massive galaxies tend to shows gradual metallicity evolution in this redshift range while massive galaxies completed their metallicity evolution at earlier cosmic epoch (see also, e.g., Savaglio et al. 2005, Erb et al. 2006). This may corresponds to the chemical version of the “down-sizing” galaxy evolution.

However, all of the above studies are for “already-evolved” galaxies; i.e., dust-unreddened populations. Recently it is pointed out that ULIRGs are significantly deviated from the standard MZR (Rupke et al. 2008, Caputi et al. 2008). Since the ULIRGs are in a rapidly evolving phase, MZRs (and its redshift evolution) for ULIRGs will give strong constraints on the galaxy evolutionary scenarios. Such studies are evidently important especially at high redshifts, where a large fraction of star formation occurred in ULIRGs (e.g., Le Floc’h et al. 2005). Note that the current metallicity measurements for ULIRGs are still relying on rest-frame optical emission lines, and thus the dust-enshrouded parts in ULIRGs have not yet examined.

A breakthrough in this issue will be achieved through MIR metallicity diagnostics for high-z dusty star-forming galaxies with using SPICA/SAFARI. Among various potential metallicity diagnostics, emission-line flux ratios using [NIII]57.2μm are promising. Specifically, the flux ratio of [OIII]51.8μm /[NIII]57.2μm is very sensitive to the gas metallicity. The simultaneous use of

[OIII]88.3μm in addition to [OIII]51.8μm and [NIII]57.2μm is even better since the density dependence of the diagnostic ratio is well corrected. This method has an advantage with respect to other NIR-MIR metallicity diagnostics using hydrogen lines (e.g., Verma et al. 2003), since the IR hydrogen lines such as Pfunt and Humphreys series lines are generally very weak. The method using [OIII] and [NIII] lines has been already applied to the ISO data to infer the metallicity of Galactic planetary nebulae (e.g., Liu et al. 2001). The superb sensitivety of SPICA/SAFARI enables us to extend such an approach toward the extragalactic universe. We already confirmed that the flux ratio of [OIII]51.8μm +88.3μm /[NIII]57.2μm works very well as a metallicity diagnostic tool also for star-forming galaxies, based on detail photoionization model calculations (Nagao, Maiolino, et al., in prep.). Note that these three lines are the strongest emission from HII regions in galaxies (i.e., excluding PDR lines such as [OI] and [CII], because they comes from different regions).

Here we mention on the detection feasibility. The [NIII]57.2μm line (faintest one among the three lines) from galaxies whose SFR is similar to M82 (Colbert et al. 1999) can be detected up to z~0.4 with SPICA/SAFARI (5 sigma detection with a 1 hour exposure). However, since ULIRGs (that are our main targets) have ~2 order higher SFRs than M82, we will detect [NIII]57.2μm (and two [OII] lines simultaneously) from ULIRGs at up to z~2. This redshift range is limited by both flux sensitivity and the wavelength coverage of SAFARI. Note that a wavelength resolution of ~1000 is adequate for this science, taking a typical emission-line velocity width of star-forming galaxies to be ~300 km/s into account.

Summarizingly, SPICA/SAFARI can measure the metallicity of ULIRGs based on reddening-insensitive MIR lines of the [OIII] and [NIII] transitions, up to z~2. This is crucial to examine the redshift evolution of the MZR for rapidly-evolving galaxies, that will then contribute to give strong constraints on the galaxy evolutionary scenarios.

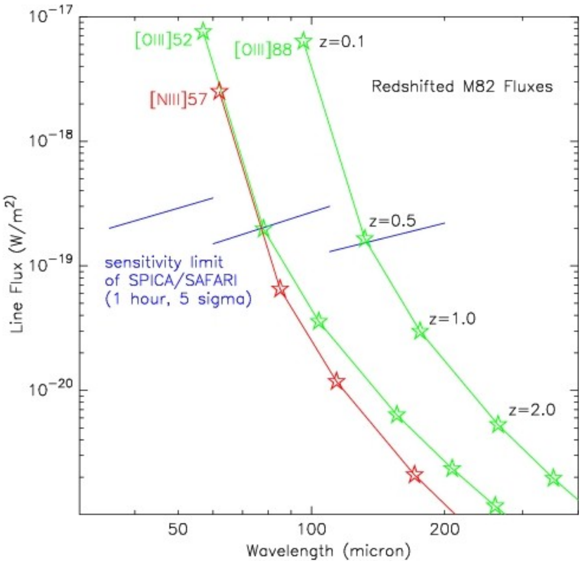


Fig.2.2-5 Flux of redshifted [OIII] and [NIII] lines (green and red curves), assuming the M82 spectrum (Colbert et al. 1999). SPICA/SAFARI 1 hour sensitivity limit is shown by blue lines. Note that our main targets are not M82-like galaxies but ULIRGs, whose SFR reaches ~100 times higher than that of M82.

Objective #4: Supermassive Black Hole Mass Growth History

In order to understand the role of supper-massive black holes (SMBHs) in galaxy evolution, we will make a systematic survey for actively mass-accreting, but elusive, SMBHs deeply buried in dust in the early universe at z>1, when both star-formation and SMBH mass growth history have peaks.

The recent discovery that (1) all spheroid galaxies (bulges and elliptical galaxies) ubiquitously contain super-massive black holes (SMBH) at their centers, and that (2) the masses of spheroid stars and SMBHs are tightly correlated, strongly suggests that star-formation in galaxies (several kpc scale) and SMBH mass growth (<pc scale, the so-called AGN activity) are closely linked. Understanding this co-evolution of galaxies and SMBHs throughout the history of the universe is one of the most important topics in present astronomy.

The cosmic energy radiation density, which is the sum of star-formation and AGN activity in the universe, is even higher in the infrared than in the UV/optical. Hence, more than half of activity in the universe is hidden behind dust. At $z > 1$, the population of ultraluminous infrared galaxies (ULIRGs; $L(IR) > 10^{12}\ L_\odot$) dominates the cosmic infrared radiation, so that distinguishing the dust-obscured hidden energy sources of the ULIRG population is directly related to clarify the history of star-formation and SMBH mass growth, and the interplay between galaxies and AGNs, in the early universe.

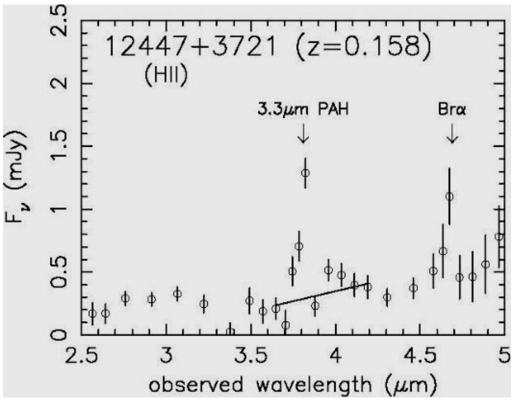
Unlike AGNs surrounded by torus-shaped dusty medium, which are classified optically as Seyferts, the putative AGNs in ULIRG’s nuclei are deeply buried (=obscured along virtually all directions), and so are very difficult to find. Infrared 3-35 μm low-resolution (R~100) spectroscopy is an effective means to investigate such optically-elusive buried AGNs in ULIRG’s nuclei. First, the effects of dust extinction are small. Second, we can distinguish between star-formation and buried AGNs, based on infrared spectral shapes (Fig.2.2-6).

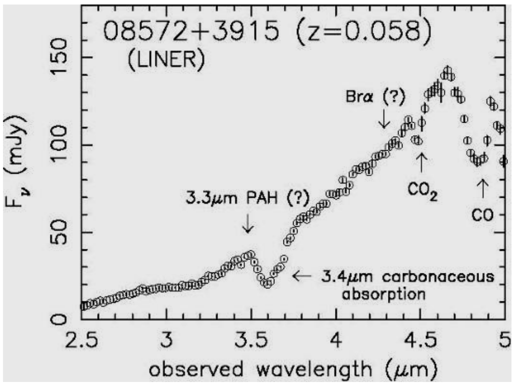
Using the Subaru 8.2m telescope, Spitzer and AKARI infrared satellites, nearby ULIRGs at z<0.3 have been systematically investigated spectroscopically, and Imanishi & his colleagues found that (1) luminous buried AGNs are common in nearby ULIRGs classified optically as non-Seyferts (HII-region or LINER types), and (2) the energetic importance of buried AGNs is relatively higher in galaxies with higher infrared luminosities, but the star-formation rates are also higher (i.e., more stars will be formed in the future) in these galaxies (Imanishi et al. 2006; Imanishi et al. 2007; Imanishi et al. 2008; Imanishi 2009).

Their results may observationally support the widely-proposed scenario that the galaxy downsizing phenomenon, where more massive galaxies with currently larger stellar masses have finished their major star-formation in an earlier cosmic age, is caused by stronger feedbacks from buried AGNs, which expel or heat surrounding gas in galaxies, stopping further star-formation on a shorter time scale.

Both star-formation and SMBH mass growth history have peaks at z>1, so that it is extremely important to directly investigate the interplay between galaxies and AGNs in this crucial epoch, using the successful 3-35 μm (rest-frame) spectroscopic energy diagnostic method. For this purpose, infrared low-resolution (R~100) spectroscopy at 6-200 μm in the observed frame (required capability for SPICA) is the most powerful, and the combination of Safari and MIRACLE onboard the cooled SPICA mission is clearly the best choice. Herschel lacks wide-band, high-sensitivity spectroscopic capability. JWST studies of ULIRGs at shorter wavelengths are severely hampered by the large effects of dust extinction. Since ULIRGs are, by definition, bright in the infrared, infrared low-resolution spectroscopy is applicable to a statistically meaningful number of distant ULIRGs at z>1 within a reasonable amount of telescope time, which is essential but prohibitively difficult at other wavelengths (e.g., (sub)millimeter energy diagnostics using ALMA; Imanishi et al. 2007). For these reasons, SPICA is clearly best suited to comprehensively understand the interplay between star-formation and AGNs in the distant universe.

To perform the scientific objectives described above, we will undertake targeted low-resolution spectroscopic observation with MIRACLE, MIRMES, and SAFARI for statistically meaningful number of mid-IR selected AGN necessary to discuss their difference with redshift, age, and the environment, etc. At the time of the launch of SPICA, not only the targets found by Spitzer, AKARI, & Herschel, but also ones found by JWST will be available. We also emphasize that the mid & far-IR blank-field survey with MIRACLE & SAFARI is quite effective to explore the dusty AGN in high-z universe, since the emission from dust torus peaks in the rest mid-IR and the mapping speed of SAFARI and MIRACLE is unprecedentedly fast to survey an area at a depth close to the galaxy confusion limit.





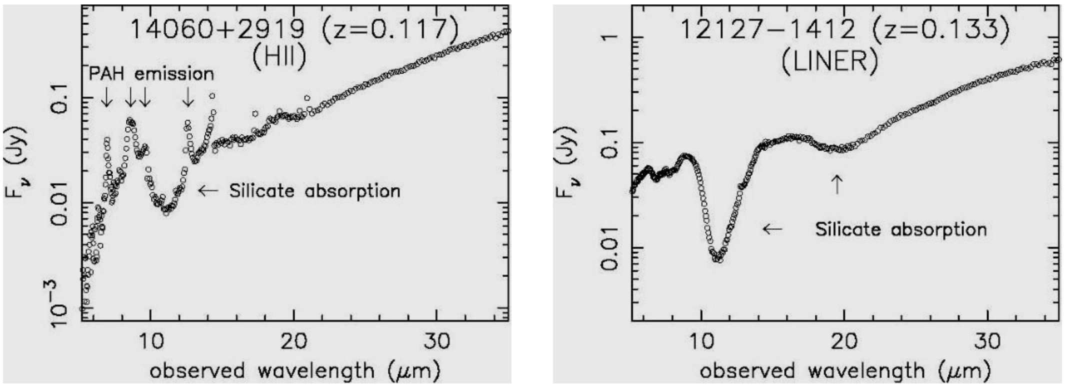


Figure Fig.2.2-6: (Left): ULIRGs dominated by star-formation activity. Polycyclic Aromatic Hydrocarbon (PAH) emission is strong. (Right): ULIRGs dominated by buried AGNs. PAH emission is invisible.

Objective #5: Cosmic Star-Formation & Mass Assembly History

We will reveal the star-formation & mass assembly history of galaxies in relation to the forming processes of the galaxy clusters and the large scale structures, as well as the environmental effect on the galaxy evolution.

Our final goal is to understand the cosmic star formation history and its relation to mass assembly history of the Universe (i.e. cluster and group formation). It is well established that cosmic star-formation rate density is clearly higher in the past Universe, showing a peak at z~1-2. However, since current surveys of the z>>1 Universe mainly utilize rest-frame UV light, it is always claimed that MIR-FIR study is essential because current surveys may have missed a large amount of "hidden" star formation activity. Therefore, looking back the distant Universe in the MIR-FIR is a fundamental but an exciting approach to understand the "real" history of the Universe.

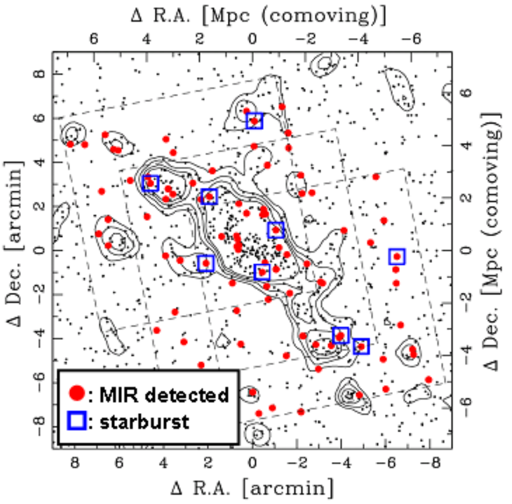


Fig.2.2-7 Spatial distribution of MIR-detected galaxies (red) around a z~0.8 cluster and starburst galaxies (squares) with cluster member distribution (small dots).

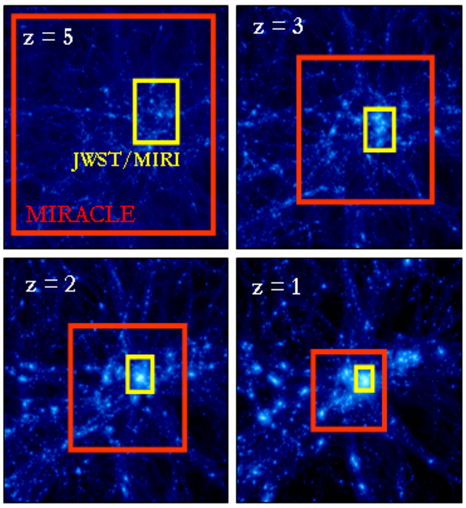


Fig.2.2-8 MIRACLE FoV with a simulation of cluster formation by Yahagi et al (2005). JWST/MIRI FoV is also shown as a comparison.

However, the situation is even more complicated because galaxy properties (e.g. morphology, colour, star-formation rate) are strongly dependent on environment. In the local Universe, galaxies in high-density environment such as clusters have little star-formation activity, but this may not be necessarily true for the distant Universe. For example, a wide-field MIR study of a distant cluster at z~0.8 with AKARI find a possible peak of star-forming activity at the "intermediate-density" environment such as cluster outskirts, groups and filaments. In fact, strong dusty starbursts are distributed along the large-scale structures around the cluster (Fig.2.2-7). This indicates that the star formation activity of galaxies may be closely related to the formation of large-scale structures of the Universe, and therefore we should explore the star formation not only in cluster or general fields but along large-scale structures at even higher redshift with SPICA.

Taking advantage of (1) wide-field capability in MIR (MIRACLE) and (2) excellent sensitivity at λ >20μm (MIRACLE/SAFARI), we can examine dusty star formation up to z~5 based on the rest-frame 7.7μm PAH emission (a good tracer of dusty star formation). We show in Fig.2.2-8 the FoV of the MIRACLE with a simulation of cluster formation. It is notable that the 6' x 6' FoV of MIRACLE can well trace large-scale structure surrounding the forming cluster at z~1-5. The most interesting targets will be "proto-clusters" at z>2, which are in the early stage of clusters where many massive galaxies are being formed and possibly tremendous amount of dusty star formation is taking place. We can detect such population (down to LIRG level) up to z~3 with MIRACLE at λ~20-40μm. Also, the excellent sensitivity at λ>40μm of SAFARI will give us a great opportunity to extend our study up to z~5. Mapping out the very active star-forming ULIRGs along high-z structures will be an exciting step and this is accomplished only with SPICA. Here, we note that we need to collaborate with wide-field ground-based survey (e.g. with Hyper Suprime-Cam to be installed on Subaru) to provide good targets of high-z structures for SPICA. At z < 2, the rest-frame 7.7μm PAH shifts to ~10-25μm where JWST is also sensitive. However, the limited field coverage of JWST makes it difficult to trace whole range of environment around a large sample of clusters (see Fig.2.2-8). We should concentrate on the surrounding region and construct a large sample of galaxies at various environments, which will allow us to identify the key environment for galaxy evolution at every redshift.

Thus, SPICA has unique advantages over other IR missions at all redshifts. We can look back on the dusty Universe across wide range of environment based on the identical tracer (i.e. 7.7μm PAH) of dusty star formation up to z~5. We will unveil the importance of hidden activity of galaxies along the cluster formation history by a wide-field survey of distant galaxy clusters (and proto-clusters) at z~1-5 and their surroundings, in comparison with a blank field survey over sufficiently large Cosmic volume (~10^6Mpc^3). This means that SPICA can construct large samples of galaxies at various redshifts and various environments very effectively. This will enable us to add the environmental axis in the plot of cosmic star-formation history (e.g. Fig.2.2-9), which is an important step towards the complete understanding of the history of the Universe.

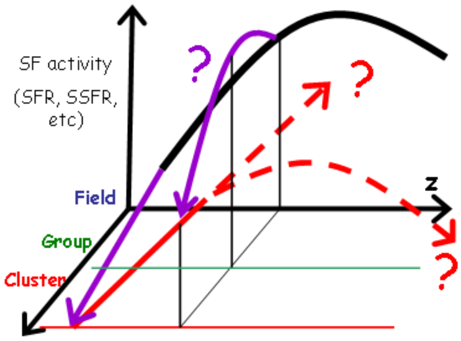


Fig.2.2-9 The role of SPICA in the objective

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2.3 Life Cycle of Interstellar Dust

Objective #1: Study of Dust-forming Supernovae

The process of dust formation by massive stars in the ejecta of supernovae in nearby galaxies is examined based on mid- to far-infrared spectroscopic observations of several (>5) supernovae in nearby galaxies to explore the origin of interstellar dust in the early universe.

Since after the detection of thermal dust emission in high red-shift universe, dust formation around massive stars has become the object of attention to explore the origin of dust in the early universe due to the effective feedback of synthesized materials into the ISM in relatively a short timescale (less than $30M_\odot$ even in low metallicity). One of the major processes of dust formation by massive stars is the dust condensation in the ejecta of core-collapse supernova (SN) explosion. The latest observations with Spitzer and AKARI reveals, however, the amount of dust newly formed in the ejecta of core-collapse SNe seems to be much smaller than that predicted theoretically. Moreover, we have little observational understanding on the composition and the properties of newly formed dust in the ejecta of SNe. Therefore, we propose here the multi-epoch mid- to far-infrared spectroscopic observations of several (>5) dust-forming supernovae in nearby (<25Mpc) galaxies within 1-2 years after the explosion. We aim to demonstrate the mid- to far-infrared spectral evolution of dust-forming supernovae in their early epoch unveiling the dust condensation process in the ejecta gas until it is cooled down to the temperature of circum-stellar pre-existing dust (~ a few hundred K).

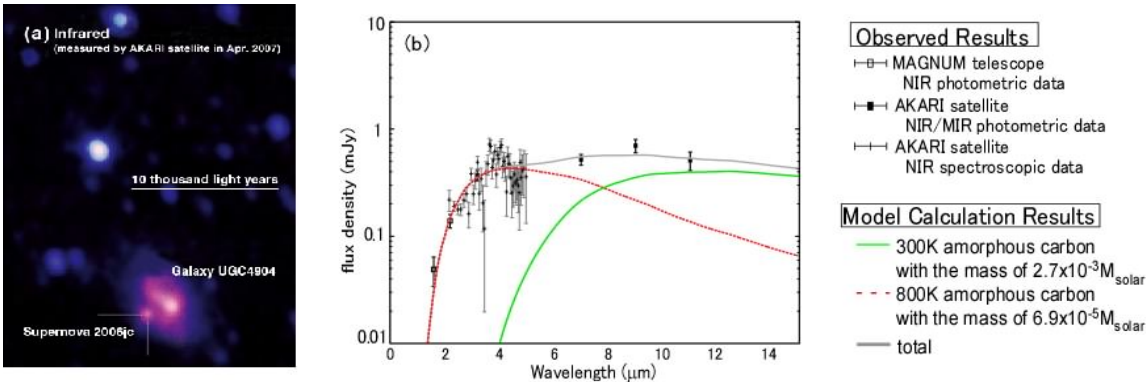

Fig.2.3-1 (a) Three false-colors composite image of the SN2006jc on 220 days after the explosion and the host galaxy UGC4904 taken with AKARI/IRC 3μm(blue), 7μm(green) and 11μm(red). (b) Near to mid-infrared spectral energy distribution of SN2006jc on 220 days after the supernova explosion. The gray solid line shows the model calculation result of dust thermal radiation. 300K amorphous carbon dust (green solid line) are found in addition to 800K amorphous carbon dust (red dotted line). (Sakon et al. 2009)

Figure 1a shows an AKARI near- to mid-infrared image of type Ib supernova 2006jc on 220 days after the explosion. The red appearance of SN2006jc in the three false-color composite image made with 3, 7, and 11μm band data indicates the presence of dust emission around the supernova. The near-infrared spectra is well reproduced by the 800K amorphous carbon dust which is regarded as the newly condensed dust in the SN ejecta. Moreover, mid-infrared photometric data indicate excess emission carried by 300K amorphous carbon dust over the thermal emission of 800K component, which suggests the dust condensation in the mass loss wind associated with the Wolf-Rayet stellar activity before the SN explosion (see Figure 1b). In order to distinguish the newly formed dust from the pre-existing circumstellar dust and to examine their compositions and the amount correctly, multi-epoch spectroscopic observations in 5-40μm with high sensitivity are crucial. The obtained datasets in this study will provide us strong constraints on the composition and the mass of newly formed dust in the ejecta of various types of SNe in nearby galaxies.

Higher dispersion (R>1000) spectroscopic abilities in the mid- to far-infrared are also effective to determine the physical condition of the circumstellar materials and to elucidate the transitions among the gas-phase materials in the SN ejecta, newly condensed dust and its precursory molecules (e.g., SiO molecules for silicate dust). For example, [SiII] line at 34.82μm and [FeII] line at 25.99μm are useful to examine the vaporization of pre-existing circumstellar silicate dust and [OIII] line at 88.4μm and [OI] line at 63.2μm are efficiently used to constrain the electron density and temperature of the emitting region. In order to distinguish the [FeII] line at 25.99μm out from the [OIV] at 25.89μm and the [FIV] at 25.83μm, spectral resolution power of R>1000 is required in the mid-infrared.

This study requires the multi-epoch mid- to far-infrared spectroscopic observations of supernovae of various types in nearby galaxies within 1-2 years after the explosion with high sensitivity in the mid- to far-infrared. Especially, high-sensitivity spectroscopic abilities in λ>20μm, where MIRMES and SAFARI onboard SPICA have the great advantages of JWST and Herchell, are crucial to achieve this project. Moreover, in order to demonstrate the mid- to far-infrared time-variance of dust and gas emission associated with the supernovae, high sensitivity spectroscopy with continuous wider wavelength coverage from 10-40μm with higher spectral resolution power of R>1000 is indispensable. We note, since the SNe are the transient phenomena, the loss of the spectroscopic ability even of overlapping wavelength regime (e.g., 10-20μm) between SPICA and JWST results in fatal fault in achieving this project.

Objective #2: Dust and Molecular Shells around Low- and Intermediate-mass Stars

Dust formation scenario by low- to intermediate-mass stars is examined based on mid- to far-infrared imaging and spectroscopy of faint dust and molecular shells around ~30 low- to intermediate- mass evolved objects to explore the origin of dust contained in the Milky Way and to understand the chemical evolution of ISM in the current universe.

Attempts to understand the dust formation scenario by low- to intermediate-mass stars are important to explore the origin of dust contained in the Milky Way and to understand the chemical evolution of ISM in the current universe. Actually, many observational and theoretical studies have investigated the properties of dust and molecular shells formed in the ejecta gas and/or in the swept-up materials around the evolved low- to intermediate-mass stars such as post-Asymptotic Giant Branch (AGB) stars and Planetary Nebulae (PNe). It is generally understood that molecules such as OH, H_2O, CO_2 and SiO form and O-rich species like silicates dust are expected to condense when the C/O ratio in the envelope is less than unity and that, on the other hand, molecules such as C_2H_2, HCN, C_2, CS and SiC form and C-rich species like amorphous carbon, SiC, MgS and PAHs are expected to condense when the C/O ratio in the envelope exceeds unity. However, the formation and chemical evolution processes of these molecules and dust grains have not yet been fully understood observationally. For example, PAH features in the mid-infrared have been observed in the post-AGB stars and C-rich planetary nebulae, but their existence and/or formation in the gentle wind of AGB stars have not yet been confirmed possibly due to the lack of ultraviolet photons from the AGB stars. For this purpose, mid- to far- infrared (5-200μm) imaging and spectroscopic observations with high spatial resolution and with sufficient sensitivity are crucial to detect the faint dust features dominantly powered by soft optical radiations in circumstellar dust shells around the AGB stars. In this study, we propose mid- to far-infrared high-resolution imaging and spectroscopic observations of faint dust and molecular shells around ~30 low- to intermediate-mass evolved stars (including AGB stars, post-AGB stars, planetary nebulae, novae etc) in the Milky Way and in the Magellanic Clouds. We aim to investigate the chemistry and dynamics of the MOLsphere and its role in the formation of dust grains and to demonstrate the mass-loss history and the formation process of molecules and dust in the mass-loss wind of evolved stars.

Fig.2.3-2 shows the schematic view of MOLsphere. MOLsphere has been detected in red giants based on ISO spectroscopic observations but no significant progress have been made since then, although it is expected as a key region to infer the mass loss and

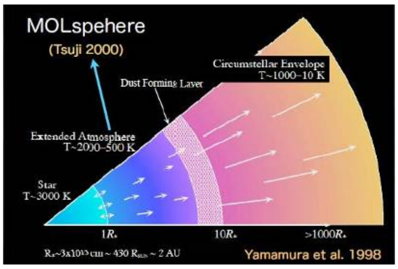

Fig.2.3-2 --- schematic view of MOLsphere (see Tsuji 2000)

the dust formation mechanisms. Especially, CO_2 (e.g., at 4.27μm and 15.2μm), OCS (at 4.89μm) and SO_2 (at 7.3μm) are important molecules to understand the chemistry and dynamics in MOLsphere and high spectral resolution (R~30000) in 4-20μm is required.

Figure 1a shows an AKARI far-infrared image of a famous red giant U Hydra. The structure of warm dust shell, which had been formed about 10^4 years before, was successfully resolved. Fig.2.3-3b shows the 8m Subaru telescope/COMICS 11.7μm image of Galactic planetary nebula BD+30°3639 and the detailed structures of PAH emission, silicate absorption as well as of hot dust continuum emission are discussed. Spatially well- resolved imaging and spectroscopy of circumstellar dust shell in mid- to far-infrared are indispensable to investigate the mass-loss history and chemical evolution (e.g. transition between C/O<1 and C/O>1) in the envelope of evolved objects.

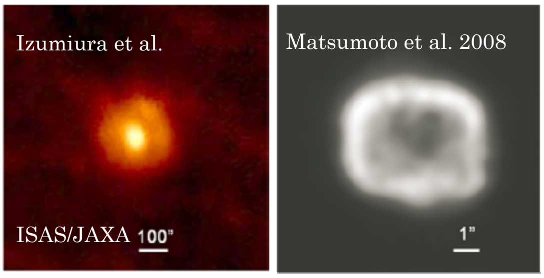

Fig.2.3-3 (a) AKARI 90μm image of the red-giant U Hydra (Izumiura et al.).
(b) Subaru COMICS 11.7μm image of PN BD+30°3639 (Matsumoto et al. 2008).

So far only a handful of bright evolved objects have been spatially resolved in the mid- to far-infrared. In order to resolve the faint diffuse dust and molecular shells around larger number of other evolved objects in the Milky Way and in Magellanic Clouds, imaging and spectroscopic capabilities with high spatial resolution and high sensitivity in 5-200μm achieved by >3m class space infrared cryogenic facility are required.

Mid- to far-infrared imaging capability with high spatial resolution and high sensitivity of MIRACLE and SAFARI onboard SPICA are quite useful to demonstrate the dynamical and chemical process in which the newly formed dust in circumstellar environment is ejected into the interstellar space. Moderate-dispersion (R>600-1000) spectroscopic abilities in the mid-infrared with MIRMES and in the far-infrared with SAFARI is crucial to examine the physical conditions and chemical composition of the circumstellar gas, molecules and dust grains around the evolved objects. High-dispersion (R>10000) spectroscopic abilities in the mid-infrared 4-20μm with MIRHES is important to examine the properties of molecules in MOLsphere of redgiant. Neither JWST nor Herchel has the sufficient capability to complete this study.

Objective #3: Dust formation and grain growth in Dense Molecular Clouds

Dust formation and grain growth in the dense molecular clouds are examined based on mid- to far-infrared spectroscopic observations of ~30 molecular clouds with embedded young stellar objects in the Milky Way and in nearby galaxies

Theoretical studies indicate that the interstellar dust is replenished by stellar dust sources (SNe, AGB stars, etc) in a typical timescale of 5×10^9 yr and that it is destroyed by SN shocks in much shorter timescale of $<1\times10^9$ yr. This suggests the existence of another dust formation sequence, which should be more effective than that occurring in the mass-loss wind of evolved stars.

Glass with Embedded Metals and Sulfides (GEMS) is a particle found in the Interplanetary Dust Particles (IDPs). Figure 1 shows the infrared spectra of GEMS in IDPs, laboratory spectra of troilite (FeS) and pyrrhotite ($Fe_{1-x}S$), and “23.5μm” band spectra found in the ISO SWS spectra of AB Aurigae and HD163296, young stars embedded in dense molecular clouds. Close resemblance among these spectra indicates the link between the dust in dense molecular clouds and the GEMS in IDPs. Since sulfur is largely depleted in dense clouds and not in the general ISM (see Fig.2.3-5), incorporation of sulfur in GEMS in dense clouds is suggested. Therefore, dense molecular clouds with embedded young stellar objects in the Milky Way and in nearby galaxies are favorable places to look for iron sulfides.

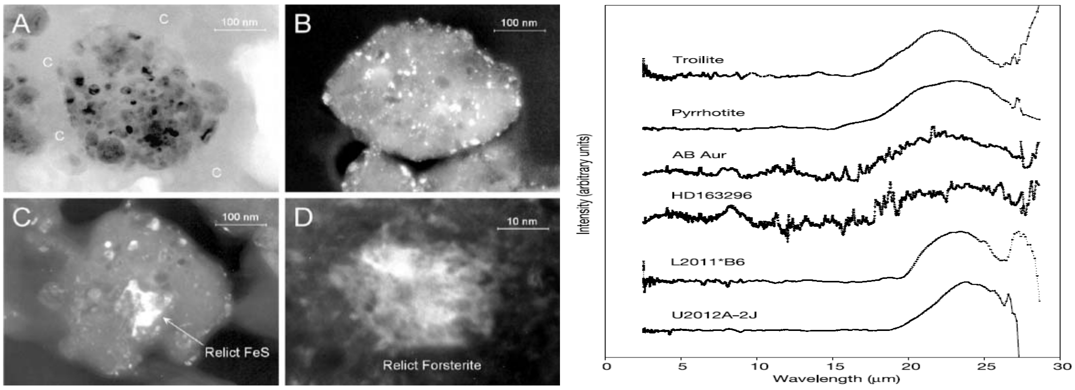

Figure Fig.2.3-4 (left panel) Glass with Embedded Metals and Sulfides (GEMS) in Interplanetary Dust Particles (IDPs) (Bradley et al. 1999). (right panel) Comparison of “23.5μm” features in laboratory infrared spectra of troilite (FeS) and pyrrhotite ($Fe_{1-x}S$), the infrared spectra of sulfide-rich IDPs (L2011*B6, U2012A-2J), and the ISO SWS spectra of two young stars AB Aurigae and HD163296 after subtracting the model spectra composed of amorphous silicates, metallic Fe and carbonaceous materials and water ice (Keller et al. 2002)

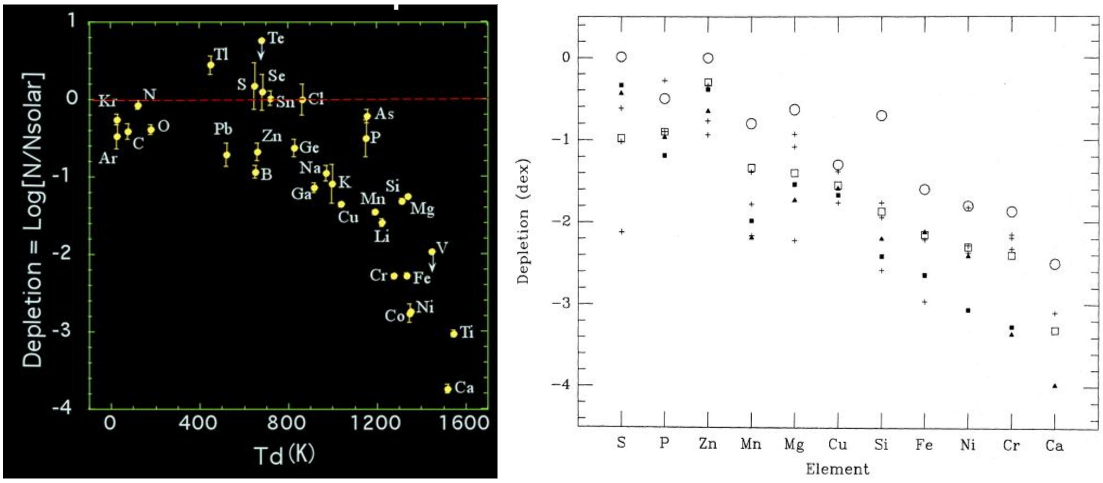

Fig.2.3-5 (left panel) Depletion of elements in general ISM. Little depletion is indicated for sulfur (Savage & Sembach 1996). (right panel) Depletion of elements in dense molecular clouds. This time, on the other hand, significant depletion is indicated for sulfer (Joseph et al. 1986).

In this study mid- to far-infrared spectroscopic observations of ~30 dense molecular clouds with embedded young stellar objects in the Milky Way and in nearby Galaxies are proposed to detect the infrared bands of iron sulfide grains and to demonstrate the connection between the GEMS in IDPs and the interstellar grains. The presence of 23.5, 34, 38, 44μm features carried by iron sulphides (e.g., troilite FeS) are searched in the mid- to far-infrared (20-45μm) spectra of dense molecular clouds, in which the enhanced depletion of sulfur to dust grains are suggested. Then we try to systematically understand the role of cold dense molecular clouds as the site of dust synthesis and/or the grain growth.

This study requires high sensitivity for diffuse emission, especially, in 20-45μm, the core spectral range of SPICA. Neither JWST nor Herschel has the required capability. Moderate-dispersion (R>~1000) and high sensitivity spectroscopic abilities in the mid-infrared (10-36μm) with MIRMES and in the far-infrared (35-200μm) with SAFARI are crucial to identify the mid-infrared features of iron sulfide grains at 23.5 μm, 34 μm, 38 μm and 44μm. High-dispersion (R>10000) spectroscopic abilities in the mid-infrared (4-20μm) with MIRHES is crucial to examine the properties of molecules in dense molecular clouds and their chemical evolution including the formation of icy mantles onto the dust grains. Especially, collaboration with ALMA project is quite useful to observationally demonstrate the detailed chemical synthesis of organic molecules on the surface of the icy mantle.

Objective #4: Study of Supernovae Remnants

The effects of supernovae on the material evolution in the universe are investigated by mid- to far-infrared imaging spectroscopic observations of about 50 supernova remnants that are detected in the infrared with spotlighting the formation and destruction of dust grains and the energy supply to the ISM.

Supernovae (SNe) are the major factory of heavy elements and play a vital role in the various key processes in the material evolution in the universe. In particular, theoretical investigations suggest that SNe make significant contributions both to the formation and destruction of dust grains. However recent observations of Spitzer and AKARI indicate that dust may not be formed efficiently in SN explosions, whereas very few observational studies have been carried out for the dust destruction by SN shocks. Infrared is the best spectral range to investigate the properties of dust grains and the interaction of SN shocks with the surrounding medium. We propose here to make a systematic infrared study of supernova remnants (SNRs) and investigate the dust formation and destruction in SNe as an important part of the study of the life cycle of interstellar dust. It is complementary to Object #1 (observation of supernovae).

SNRs show complicated structures in the infrared. Fig.2.3-6(a) shows an AKARI mid-infrared image of the young oxygen-rich SNR G292.0+1.8. The ring-shaped structure seen in the middle of the image (ER) comes from the emission of dust grains formed before the SN explosion. The emission from dust grains associated with the SN ejecta appears clearly in the 15 to 24μm band intensity ratio map (b). Fig.2.3-6(c) shows the spectra of the ejecta, indicating the presence of a broad feature around 18μm that contributes to the increase in the band ratio. Other oxygen-rich SNRs also indicate the presence of a broad feature in 18–23μm region, suggesting common properties of dust grains

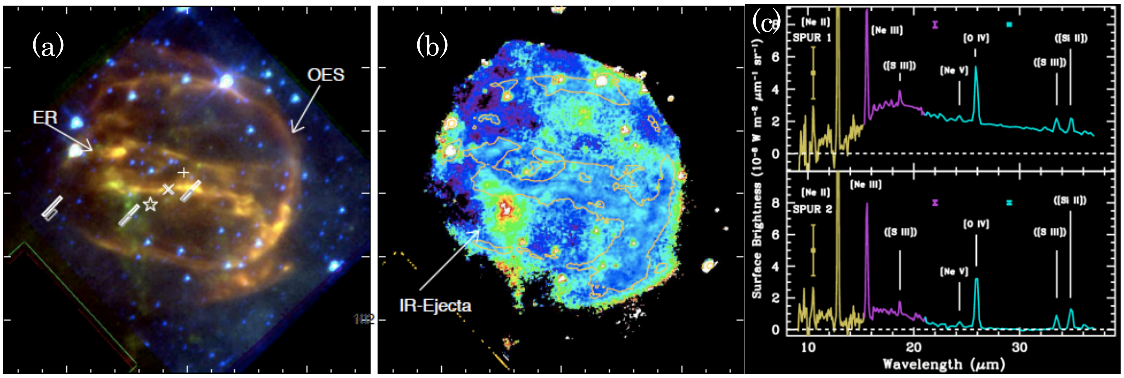

Fig.2.3-6 AKARI 7, 15, and 24µm artificial color image (a) and the 15 to 24µm band intensity ratio (b) of SNR G292.0+1.8 (Lee et al. 2009). The SN ejecta is clearly seen in the ratio image. (c) Spitzer IRS spectra of the ejecta in G292.0+1.8 (Ghavamian et al. 2009). A broad feature is seen around 18µm.

associated in SN ejecta, but no firm identification of the carriers have so far been established. These observations demonstrate the importance of high-spatial resolution observations to separate each component and extract the emission from the SN ejecta and the significance of medium-resolution spectroscopy of SNRs to correctly understand the nature of the infrared emission and dust properties in the SNRs. Similarly high spatial resolution is strongly required in the far infrared to fully understand the nature of SNR emission and investigate the presence of cold dust associated with SNRs. A wide spectral coverage from the mid to far infrared is crucial to understand spectra of SNRs that consist of dust bands as well as emission lines. Full infrared spectra of the interacting region of SN shocks (a shell-like emission in Fig.2.3-6(a)) are also important to study the size distribution of dust grains and thus the dust destruction process.

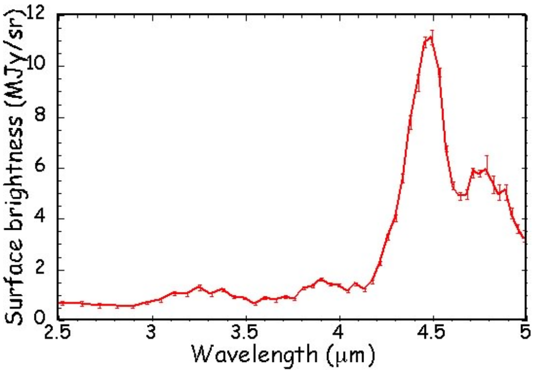

Fig.2.3-7 AKARI spectrum of a knot in the Cas A SNR. CO gas emission feature in 4.4–4.7μm is clearly seen.

Spectroscopy also tells us gas chemistry taking place in the ejecta as well as in the interacting gas. Fig.2.3-7 shows an infrared spectrum of a knot in the Cas A SNR, suggesting the presence of CO gas. The detection of CO gas is significant since some theoretical work predicts direct condensation of carbonaceous dust from carbon gas without forming CO. If CO is formed in the ejecta, the formation of carbonaceous dust is largely reduced. Similarly, observations of SiO gas band around 8μm are valuable for the study of silicate dust formation. High-resolution spectroscopy of these bands enables us to make detailed investigations of the physical conditions and gas chemistry in SN ejecta. High-resolution spectrograph in the 4–8+α μm region thus provides unparalleled information on the study of dust formation process in SNe.

This study requires high sensitivity for diffuse emission from the mid- to far-infrared, the core spectral range of SPICA. Neither JWST nor Herschel has the required capability. High spatial resolution in the mid to far infrared is indispensable to separate the various components and spectroscopic imaging capability for an arcminute scale is important. Imaging spectroscopy capability with sufficient spatial resolution and high sensitivity for diffuse emission of MIRACLE, MIRMES, and SAFARI onboard SPICA provides the unprecedented opportunity to execute this study.

Study of Young Core-collapse Supernova Remnants with FPC-S

We propose FPC-S spectral mapping of young core-collapse SNRs in the Galaxy in order to study the SN explosive nucleosynthesis and explosion process. The explosion of core-collapse supernova(SN) is known to be asymmetric and turbulent, but the physical mechanism and the explosion process remain to be largely unknown. The young Galactic SNRs provide an unique opportunity to study the detailed spatial and kinematical distribution of ejecta. For example, in the 3,000-yr old SNR G11.2-0.3, [Fe II] emission line observations revealed that the Fe ejecta from the innermost layer of the explosion are both spatially and kinematically asymmetric (Koo et al. 2007, Moon et al. 2009). The Fe ejecta do not show other heavy elements which indicates the production without intense microscopic material mixing as in alpha-rich freezeout process. A similar asymmetric distribution of ejecta has been observed in another young SNR G292.0+1.8 using the AKARI infrared space telescope (Lee et al. 2009). The LVF observation can provide unprecedented information on the distribution of ejecta material produced in core-collapse supernova explosion as well as that of the circumstellar material from progenitors.

There are many important elements of the ejecta and circumstellar material that can be observed in the near-infrared wavebands. The ejecta usually have significant amount of Fe, S, Si, O, and/or He from the supernova nucleosyntheses, and all of them have bright emission lines in the near-infrared wavebands. H, H_2, and/or He from the circumstellar material of the progenitors also have strong near-infrared transition lines. Considering that young core-collapse SNRs are located in the Galactic plane where there are numerous stars overlapping, it is critical to subtract out the stellar radiation using the nearby continuum emission to identify the line emission of the ejecta and circumstellar material. The LVF spectral mapping naturally provides such a capability of obtaining nearby continuum emission with the same point spread function of the line transitions.

Objective #5: Interstellar Medium in Nearby Galaxies

By mid- to far-infrared imaging spectroscopy, we spectrally decompose and spatially resolve emission from the ISM in 50 nearby galaxies of our AKARI sample, to track galactic-scale material circulation from sources to sinks of the ISM in galaxies.

The physical processing and chemical evolution of the ISM in galactic scales are examined in view of material circulation within nearby galaxies. From this viewpoint, “sources” of the ISM include SNR, giant molecular clouds, environments around evolved stars, outflows from galactic nuclei, accretion of intergalactic matters, and mergers of galaxies, while “sinks” of the ISM are such as shocked regions, nuclear activities in jets and X-ray, hot plasmas, and galactic outflow. By spatially resolving these components from diffusely extended components, we track the large-scale transmigration of dust and the gradient of ISM properties within a galaxy. Since the evolution of dust highly depends on the phase of associated gas, we spatially decompose the phases of molecular, atomic (including PDR), and ionized gases by spectral line diagnostics to obtain the density and temperature of gas. With MIRACLE and SAFARI, we derive large-scale spatial information over a whole galaxy, while MIRMES probes local regions such as galactic nuclei (and SSCs) to study the properties of LINERs and nuclear starburst as well as the effects of nuclear activities on ambient materials.

The wavelength range of 20-200 micron, in which SPICA has high sensitivities, is suitable for study of the ISM associated with high-energy phenomena such as shocks, plasma/X-ray heating, galactic super-wind, and nuclear jets, providing knowledge complementary to cold matters (Herschel, Planck, and ALMA) and stars and PAHs (JWST). In particular, the 35-55 micron range that neither Spitzer nor Herschel can cover is the key to understand spatial variations in the chemical composition (silicate, carbonaceous) and size distribution (sputtering, fragmentation, aggregation) of dust.

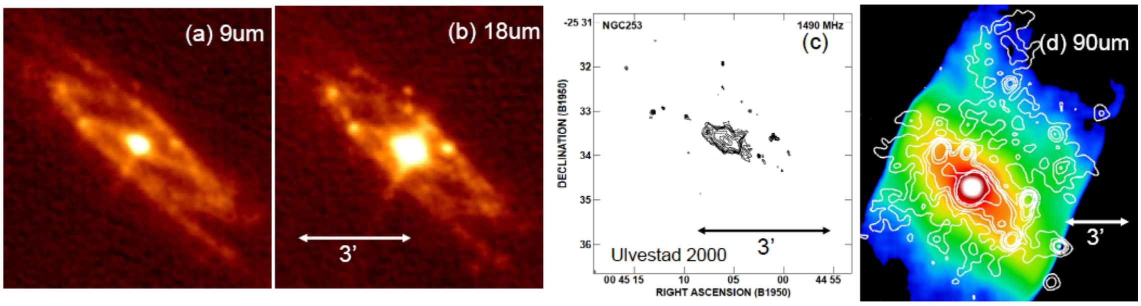

Fig.2.3-8 Edge-on disk galaxy NGC253. (a) AKARI 9um (PAH+old stars). (b) 18um (warm dust). (c) VLA 20 cm continuum. Discrete radio sources: SNRs? HII regions? (d) AKARI 90um in color, ROSAT X-ray in contours. Dust outflow entrained by X-ray superwinds.

The objective can be categorized into two big themes: (1) 3D picture of ISM distributions in various gas phases, and (2) galactic nuclei and influence of their activities on ISM, AKARI examples of which are shown in Fig.2.3-8 and Fig.2.3-9, respectively. For the former, MIRACLE and SAFARI (low-res.) enable spatially-resolved spectroscopic studies of dust and gas in disks and haloes for face-on and edge-on galaxies. For the latter, MIRMES and SAFARI (high-res.) probe central regions of galaxies by detailed gas line diagnostics, even revealing the kinematics of material circulation flow.

Based on our AKARI nearby galaxy sample, we carefully select 50 target galaxies for SPICA, which have sizes of 5-10 arcmin with various morphological types. We require 600 hrs in total, the breakdown of which is 4, 1, and 7 hrs per galaxy for MIRACLE, MIRMES, and SAFARI, respectively. In the final decision of target selection, we will, of course, account for new knowledge to be revealed by upcoming observatories such as Herschel, JWST, and ALMA.

Why do we need SPICA other than Herschel and JWST? There are mainly two reasons: (1) low FIR background thanks to the cold telescope enables faint extended emission to be detected from nearby galaxies, which Herschel cannot detect. (2) Small and simple PSFs in the MIR-FIR thanks to the monolithic 3.5m mirror can reliably resolve various dust and gas components in nearby galaxies.

Our requirements for SPICA are as follows:

(1) MIR-FIR continuous spectral coverage is crucial for dust physics, maximizing outputs from the cold telescope; this would make SPICA unrivalled.

(2) MIR-FIR spectroscopic imaging capability with low - moderate spectral resolution is essential for spatially-resolved studies of nearby galaxies.

(3) For efficient mapping, we need the capability of raster mapping with variable integration time at different positions.

(4) For better calibration of extended sources, [SiII] 34.8 μm line should be observed by both SAFARI and MIR instruments with matched spectral capabilities. Two different modes are compared: imaging FTS and long-slit spectral mapping.

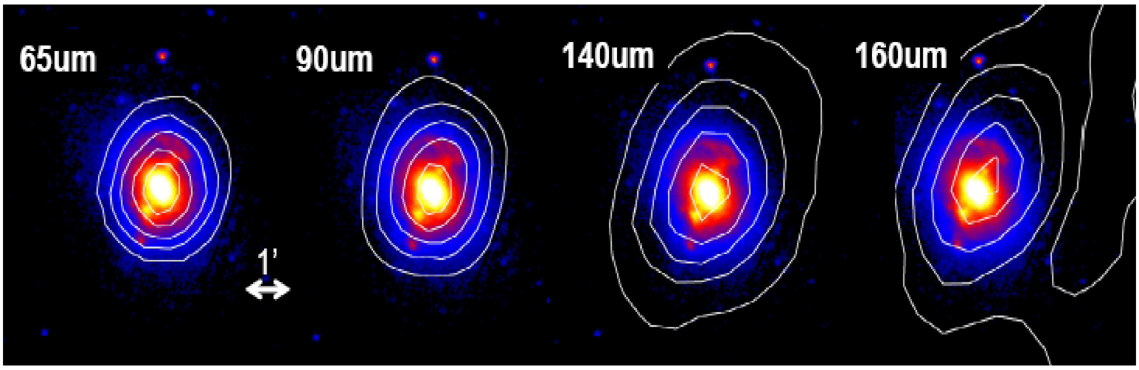

Fig.2.3-9 : LINER elliptical galaxy NGC1316. AKARI/FIS 4-band contours overlaid on AKARI 11um image. Energy feedback outflow from a central dust reservoir (Temi et al. 2007)

Objective #6: Imaging and Spectroscopic Survey of Galactic Plane

Structures and constituents of the Milky Way are illustrated in detail by exploiting an imaging survey covering the region of $-90^{o}<l<+90^{o}$ and $-2^{o}<b<+2^{o}$ in several mid-infrared bands and a spectroscopic survey covering the region of $-60^{o}<l<+60^{o}$ and $-1^{o}<b<+1^{o}$ in the mid-infrared. The life cycle of the interstellar medium in the Milky Way is examined on a galactic scale in terms of the activities of low-mass to massive stars.

For the thorough understanding of the circulation and physical/chemical evolution of matter in the Galaxy, we need to know the distribution of each population of mass-losing objects, including low-mass RGB and AGB stars, massive Wolf-Rayet stars, luminous blue variables, supernovae, and so on. High mass-loss rate stars that are preferentially found near the Galactic center may dominate the mass and dust return rates in that local space.

Besides, knowledge on the shape of the Galaxy, as a result of the synthesis of all kinds of stellar populations, is also indispensable for understanding the matter circulation in the Galaxy. It is well accepted that our Milky Way Galaxy is a spiral galaxy with a thin disk of stars and gas rotating about the Galactic Center. There are accumulating pieces of evidence that the Milky Way Galaxy has a bar structure in its center (Binney et al. 1991; Blitz & Spergel 1991; Nakada et al. 1991; Stanek et al. 1994) and the bar may have an additional finer structure (Nishiyama et al. 2005, Fig.2.3-10, and references therein). GLIMPSE surveys with the Spitzer Space Telescope (Benjamin et al. 2005, Fig.2.3-11) revealed a stellar bar structure in the near-side of the Galactic disk with respect to the Galactic Center. Their survey, however, suffers source confusion that hampers the detection of the far side of the bar structure. Also, the stellar spiral pattern of the Milky Way Galaxy still remains controversial (e.g. Benjamin et al. 2009).

To obtain a correct view of the distribution of dust-supply stellar sources in our Galaxy we propose to make a MIR Galactic plane survey with SPICA. The MIR (Mid-Infrared), the essential waveband for the census of mass-losing objects in the Galaxy, is not accessible with coming cutting-edge facilities such as Herschel or ALMA. The proposed survey consists of imaging and spectroscopic observations. Spitzer GLIMPSE survey (Benjamin et al., 2003) has a limiting magnitude of 0.4 mJy at 4.5 μm (Mead et al., 2005). It is also confused with sources in the Galactic plane. The flux of red clump stars at the other edge of the Galactic disk is estimate to be about 70 μJy (5 σ) at 5 μm, including the interstellar extinction. The source density down to this flux level is extrapolated from GLIMPSE data (Benjamin et al., 2005) to be 0.2 sources in one arcsec^2. Therefore SPICA survey will not be limited by confusion. The flux level of 70 μJy should be reached in a net integration time of 3 sec with MIRACLE. Ergo, the imaging survey to detect all red-clump stars in our Galaxy can be completed in a relatively short time if an efficient survey capability of SPICA is equipped. For the imaging survey we propose to cover the region of $-90^{o} < l < +90^{o}$ and

$-2^{o} < b < +2^{o}$. We also propose to make about 10 repeated observations to monitor the variability. The imaging survey will provide us with the structure of our entire Galaxy, including the bar, bulge, and arms and the distribution of dust supplying sources in our Galaxy. We expect to detect one billion sources in this survey. In addition, a supplemental imaging survey of the same region at ~4μm with a similar sensitivity with FPC-S will further enhance the scientific capabilities of the MIRACLE imaging survey, if available. The wide field of view of SPICA is a great advantage to other mid-infrared space missions with a comparable spatial resolution.

The spectroscopic survey makes use of the multi-slit of MIRACLE and obtains spectra for the region of $-60^{o} < l < +60^{o}$ and $-1^{o} < b < +1^{o}$. With the net integration time of 3 sec per slit position, we would like to reach 600 μJy (5 σ) at 5 μm. Again we need an efficient slit scan capability with MIRACLE of SPICA, which would be a tough requirement for SPICA. The spectroscopic survey is expected to detect one million sources, including very luminous red objects, which allows us to obtain the distribution of mass-losing massive stars in our Galaxy for the first time. It will also provide a complete diffuse emission map of the Galactic plane. Combining the results of this survey with the detailed study of SNe, SNRs and low-mass evolved stars, we will be able to obtain the full understanding of the contribution of each stellar source to the dust supply at every position of the inner part of our Galaxy. The planned multi-slit function in spectroscopy of MIRCLE makes SPICA a unique space mission at mid-infrared.

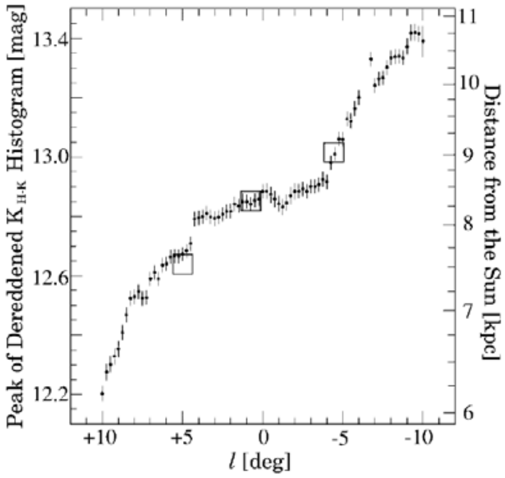

Fig.2.3-10 Peak magnitude of red clump star counts against the Galactic longitude (Nishiyama et al.2005). Changes in the slope of the plot indicate the presence of an inner structure in the central bar of the bulge.

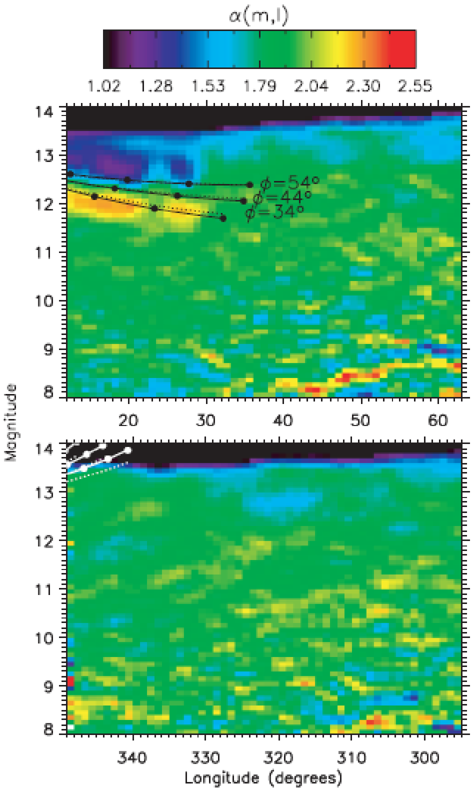

Fig.2.3-11 Power-law exponent of source counts as a function of flux density, plotted as a function of the Galactic longitude and apparent magnitude (Benjamin et al. 2005). Upper panel: Positive longitude, lower pane: Negative longitude. The features in yellow-orange and dark blue together in the upper panel indicate the detection of a central stellar bar.

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2.4 Studies of Exoplanets and Solar Systems

Objective #1: Direct Detection and Characterization of Exoplanets

To understand the diversity of the exo-planetary systems, we will attempt direct detection and characterization of exoplanets in the infrared wavelengths. Complement al two methods, coronagraphic observation and planetary transit monitoring, are described as key observations.

(Introduction)

The solar system including the Earth;
Is such a system unique in the Universe, or is it commonplace?
How is such a planetary system born and evolved?

We consider these are ones of the most important questions for space science in the near future, potentially connected to the search of the origins of life. Since the first report by Mayor and Queloz (1995), more than 300 exoplanets have been found. However, most of the detections are by indirect methods, e.g., detail monitor observation of radial velocity of a mother star. For the next step, we need observations which make the systematic characterization of Jovian exoplanets (one of the most major elements of planetary system) possible. When such characterization is attempted, usually huge contrast between a mother star and a exoplanet is critically serious problem.

(Observation requirement ; Why SPICA?)

The contrast is relaxed in mid-infrared wavelength rather than optical wavelength because of thermal infrared emission from a planet as shown in Fig.2.4-1, which also shows there are important spectral feature of Jovian exoplanets in mid-infrared. So the capability of mid-infrared (>3.5 μm) observation is needed. For the characterization (not only the detection) of the exoplanets, we require spectroscopy with the spectral resolution of 20-200 in order to measure spectrum of exoplanets including features of CH_4, NH_3, H_2O and so on. To improve sensitivity in order to observe old (a few Gyr) Jovian planets in shorter wavelength than 5um, it's preferable to use a InSb detector together with a Si:As detector. HERSCHEL does not have sensitivity in mid-infrared. Mid-nfrared sensitivity of groud-based giant telescopes of the next generation (e.g., TMT) is quite limited because of huge infrared emission from the sky and telescope itself. After all, only JWST can be a rival of SPICA. Strategy to go over JWST is described below with each observation method.

Coronagraphic observation

Direct imaging and spectroscopy by a coronagraph is the most straightforward way to the detection and the characterization of the exoplanets. Recent papers reported the success of direct imaging of several exoplanets (Marois et al. 2008, Kalas et al. 2008, Fig.2.4-2) using ground based telescope with adaptive optics and *Hubble Space Telescope* (*HST*) in near-infrared and optical wavelength. However, such examples are strongly limited in only luminous planets far from the mother star and spectroscopy is not achieved. These examples make significance of SPICA coronagraph more sure because they do provide evidences of existence of targets, and concrete information of detection for upcoming characterization with SPICA. For SPICA coronagraph, required contrast in PSF, and inner working angle is 10^{-6}, and 3.3lambda/D, respectively, to perform coronagraphic observation for significant number of (~100) targets. Broad bandpass filters are needed for the coronagraphic imaging mode. Major advantage of SPICA coronagraph over JWST's one are 1)Thanks to the clean PSF by monolithic telescope mirror and active optics, the contrast of SPICA coronagraph will be ~10times higher than JWST's. 2)Continuous wavelength coverage of spectroscopy. Use of InSb detector together with Si:As detector is also useful for differential observation in two closed bands simultaneously, which improves contrast by image subtraction.

Monitor observation of the planetary transit

Another hopeful way for the characterization of spectrum of the exoplanets is the monitor observation of the planetary transit. It was shown by observations with SPITZER space telescope that absorption feature by atmosphere of an exoplanet is detectable by non-spatially resolved monitoring of transiting planetary system (e.g., Deming et al. 2005). Recently detection of important features, e.g., H_2O, are reported (e.g., Tinetti et al. 2007). At current succeeded targets of such observation are limited "hot Jupiter". SPICA can extend the targets of spectroscopic study of planetary transit toward smaller planets vastly because of photon gathering power by larger telescope aperture than SPITZER. To realize systematic study by this method, spectroscopy with R~200 or more is needed. Strategy to avoid saturation in the detector and achieve high duty-cycle is important. Stability of the observing system is essentially important. The coronagraph instrument with coronagraph-mask removed mode (i.e., fine-pixel camera mode) can be also useful tool for this purpose, in which instrument design against the saturation problem (e.g., defocusing function) and internal calibrator will be adopted. InSb detector extends spectral coverage of this observation to near-infrared region. Instrument designed considering saturation problem, stability calibration, and simultaneous wide-spectral range monitoring by two detectors can be advantage of SPICA over JWST for the planetary transit monitoring. Targets of this study have to be discovered before. Space telescopes, COROT, Kepler, and projects using ground-based telescopes will provide much enough number of detection of planetary transit via ongoing or upcoming operation. The coronagrahpic observation and the planetary transit monitoring are complementary because the former and later method is suitable for distant and closed planet from the mother star, respectively.

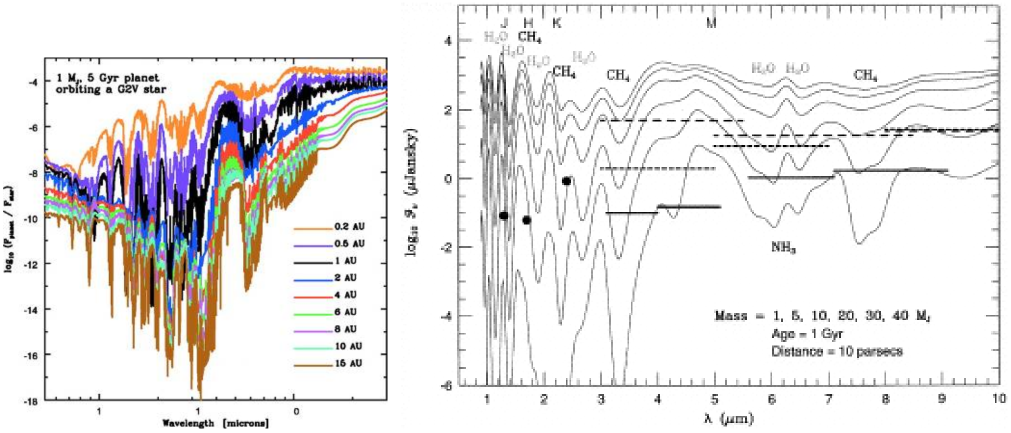

Fig.2.4-1 Spectrum of Jovian exoplanets derived by simulation (left: Burrows et al. 2004, right: Burrows et al. 1997)

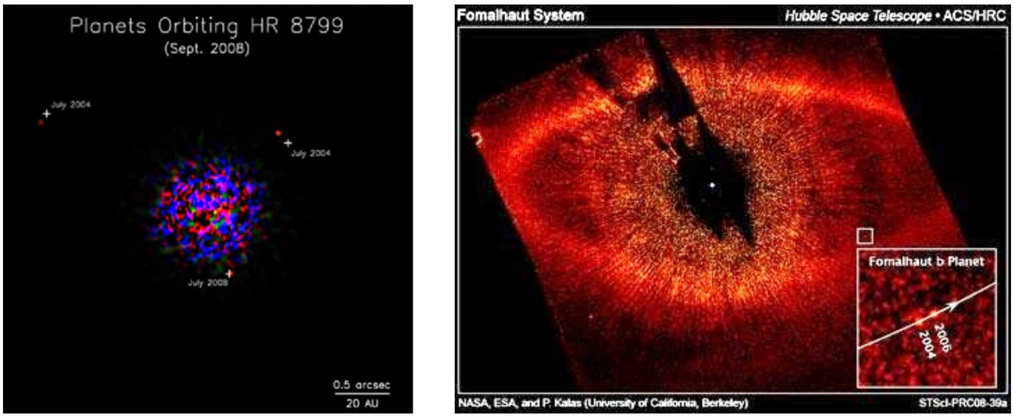

Fig.2.4-2 Directly imaged exoplanets. (left: Marois et al. 2008, right :Kalas et al. 2008)

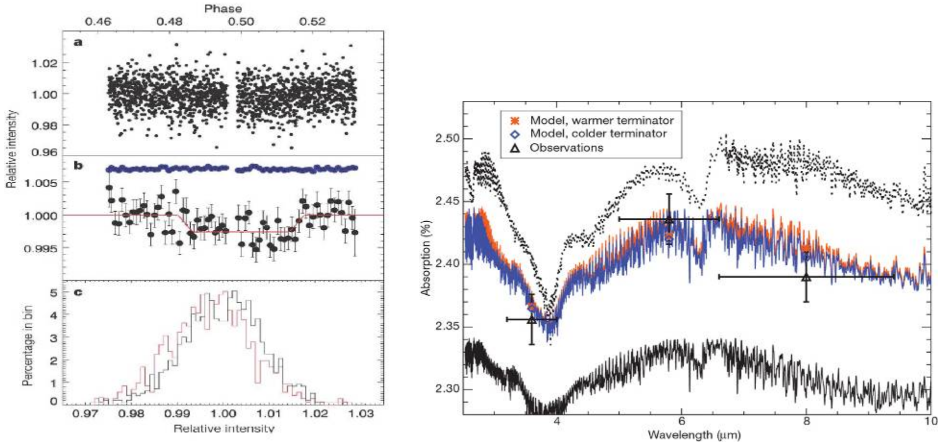

Fig.2.4-3 Left: Planetary transit data to derive infrared spectrum feature (Deming et al. 2005). Right: Spectral features of an exoplanet derived from the transit monitor detecting H_2O (Tinetti et al. 2007).

Objective #2: Dissipation of Gas from Proto-planetary Disks

> We will reveal the formation mechanism of gas giant planets and initial condition of terrestrial planet formation, by observing the dissipation of gas and their structural evolution in planet-forming regions.

For the last decade, more than 300 gas-giant planets have been discovered by measuring the radial velocity of parent stars. It is intriguing that many of them have orbital period much shorter than Jupiter on our solar system, and also a variety of orbital eccentricities. In contrast, coronagraphic imaging at optical and near-IR wavelengths have revealed promising candidates of extrasolar planets, whose orbital scales are larger than Jupiter. Forthcoming space missions like Corot and Kepler would even discover a number of terrestrial planets in the next several years.

The best examination of their formation and evolution theories require the observations of circumstellar disks in active planet-formation. The evolution of the disk at r=1-30 AU is of particular interests for investigating planet formation like our solar system, orbital migration of gas-giant planets, and formation of extrasolar terrestrial planets. Spectroscopic capability of SPICA (MIRMES, MIRHES, SAFARI, BLISS) will provide an excellent opportunities for observing ***gas*** in such regions. Such studies are complementary with (1) ongoing studies of disk structured by measuring spectral energy distribution of gas disks; (2) ALMA, which will allow us to resolve the structure of dust disks at AU scales in nearest planet forming regions; and (3) JWST, whose spectrographs have unprecedented sensitivity at $\lambda<20$ μm with a spectral resolution up to R=3000.

The gas comprises most of the initial disk mass and may consequently play an important role in the formation and evolution of planetary systems. It would allow gravitational instability to occur for the formation of gas-giant planets (e.g., Boss 2003), or provide gas drag on rocky materials, determining the mass and orbital eccentricities of terrestrial planets (e.g., Kominani & Ida 2002). So far, observational studies of gas disks have been conducted mainly through radio interferometry and ground-based optical-IR spectroscopy. The former technique allows us to observe regions on a few hundred AU scale (Dutrey et al. 2007), while the latter allows us to observe regions within a few AU from the central star (Najita et al. 2007). Recent advances in mid-to-far IR spectroscopy have allowed us to explore the gas at intermediate radii from the star (i.e., 1-30 AU), the key zone for understanding planet evolution. Such studies to date include: (1) Spitzer spectroscopy of atomic ([Ne II], [Fe II] etc.) and molecular lines (H_2O, OH, HCN, C_2H_2- e.g., Lahuis et al. 2007; Carr & Najita 2008; Salyk et al. 2008) and (2) ground-based observations of [Ne II] and H_2 17 μm (e.g., Herczeg et al. 2007; Bitner et al. 2008)[5]. The spectrographs discussed for SPICA are well optimized to extend such research to truly discuss the evolution of gas disks due to planet formation.

MIRMES, SAFARI and BLISS would detect emission lines over a wide-spectral range (10-200 μm) at an unprecedented sensitivity, being free from telluric absorption. The coverage of these spectrographs include a variety of atomic/ionic/molecular lines expected from the protoplanetary disks (Fig.2.4-4). This would allow us to measure the total mass of gas with many young stars with a variety of evolutionary phases. As a result, we would be able to determine the dissipation time of the gas disk at 1-30 AU, and its relationship with stellar mass and binarity. Such observations would provide crucial information for identifying the formation mechanism of gas-giant planets, and initial conditions of terrestrial planet formation.

MIRHES would be sensitive to the profiles of various emission lines, leading to the determination of physical/chemical conditions as a function of radius. To facilitate this, its spectral coverage is designed to observe a variety of emission lines (CO, H_2O, HCN, CO_2, C_2H_2 etc.) at 4-8 and 12-18 μm. This would allow us to observe how the structure of gas disks evolve due to planet formation (Fig.2.4-5).

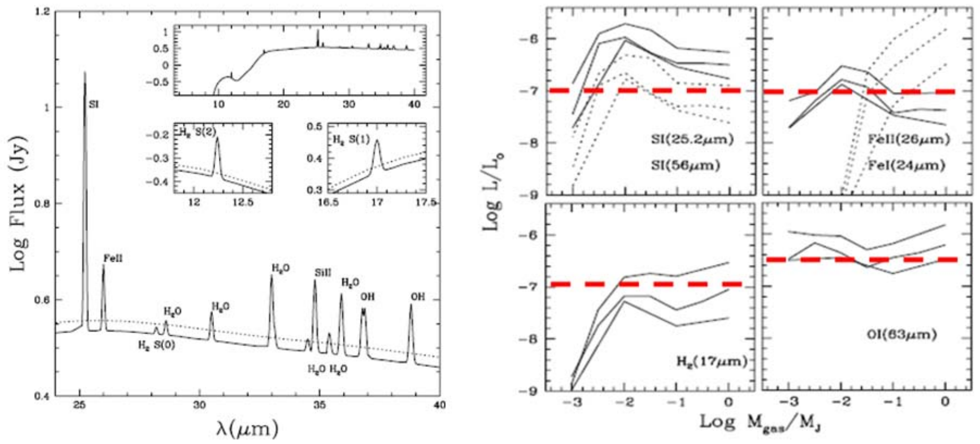

Fig.2.4-4: modeled spectrum of a relatively evolved protoplanetary disk (M~1 M_{solar}, t~10 Myr, left), and predicted line fluxes as a function of gas mass (right) (Gorti & Hollenbach 2004). The red dashed lines indicate the sensitivity of SPICA (1 hr, 5-σ at 140 pc).

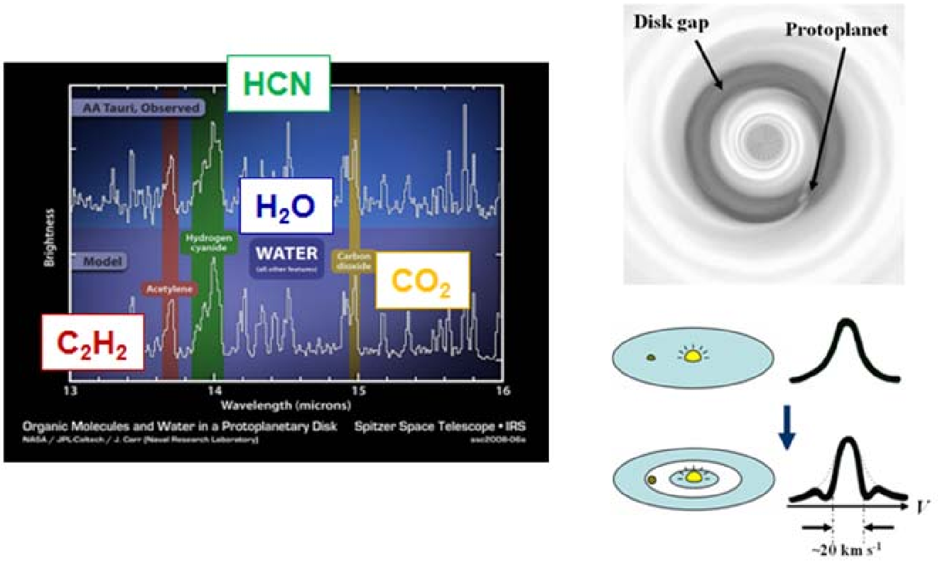

Fig.2.4-5 (left) a variety of molecular lines associated with a protoplanetary disk. Adapted from Spitzer Press Release. (top-right) Numerical simulation for a protoplanet tidally interacting with a

protoplanetary disk and opening-up a disk gap (Bryden et al. 1999). (bottom-right) Schematic view of how the disk clearing due to a proto-Jupiter would change the emission line profile.

Objective #3: Debris Disk Surveys

We reveal the similarity or diversity of extrasolar systems by observing a number of debris disks, which are much more easily observable than exoplanets.

Not only the molecular gas but also dust grains play the key roles in the evolution of circumstellar disks and the planet formation, since all planets are thought to form in the accretion disks that develop during the collapse and infall of massive dusty and molecular cocoons larger than ~10 000 AU where stars are born.

The young disks are very optically think in dust, with high radial midplane optical depths in the visual ($\tau_V >> 1$). These protoplanetary disks then start to become optically thin ($\tau_V \sim 1$) in a few million years after formation and evolve into transitional discs as their inner regions begin to clear at >10 Myr. Disks with ages above >10 Myr are thought to be practically devoid of gas (Duvert et al. 2000) and the dust in these older debris disks is generally not primordial but continuously generated "debris" from planetesimal and rocky body collisions. At this stage, the disk becomes very optically thin ($\tau_V << 1$). Debris disks are thus younger and more massive analogs of our own asteroid (hot inner disk, Td ~200 K) and Kuiper belts (cool outer disc, Td =~ 60 K), so their study is vital to place the Solar System in a broader context.

SPICA is also capable to survey existence of such dust disks in our Galaxy, with extremely high sensitivity in the mid and far-infrared.

Debris Disk Survey in the Solar Neighborhood

A number of dusty debris disks have been discovered to date since the initial IRAS identification of an infrared excess from the A-type main-sequence star, Vega. While most pre-main sequence stars host a dust disk, a recent census by Spitzer Space Telescope suggests that 10-15 % of nearby main sequence stars host such disks, independent of spectral types. They have given very important information on what is happening during early stage of planet forming processes. However, they comprise only a small portion of the whole extra-solar systems: debris disks discovered so far are very bright ones due to limited capability of the telescope/instruments.

SPICA's unique capabilities of high sensitivities at FIR and a coronagraph at MIR enable us to detect debris disks around nearby normal stars as faint as our Solar system's by imaging observations. It may not be easy to detect Zodiacal light equivalents around Asteroid Belt even with SCI due to the limited spatial resolution. However, since all the extrasolar planetary systems do not always have the identical architecture, it is worth trying to detect debris disks in the MIR with SCI. Kuiper Belt debris should be detected with SAFARI if it is equipped with a simple coronagraph. The faint debris is most likely produced by mutual collisions of less disturbed small bodies like our own, and provides us with clues on current status of planet formation. The location (radii) of the debris disks (rings) give clues to current disposition of planets. Although they may not be direct evidences of the presence of plants, we can obtain a lot of circumstantial evidences for the architecture of the extrasolar planetary systems.

Targets are almost all normal stars (of about 30-50) closer than a certain distance which is < 5pc. They should be chosen from the latest list of nearby stars before the observations.

A coronagraph mask is required to overcome possible limited dynamic range of SAFARI.

Statistical Study of Debris Disks around Early type Main-Sequence Stars

The number of detected debris disks is increasing but is still far from satisfactory when making statistical discussions. The sensitivity of SPICA at FIR will be higher than AKARI and Spitzer by a factor of 10. Thus, it will potentially increase the sample of debris disks dramatically. However, just a high sensitivity is not enough to detect faint debris disks because a debris disk is detected as an excess over the stellar photospheric emission. In order to detect small excess emission, photoshperic emission should be accurately estimated based on the observations at shorter wavelengths and model stellar atmospheres but the accuracy is at best only a few percent. Below this level, it is detection of excess emission is not practical even if the sensitivity is high enough.

Therefore, best strategy utilizing high sensitivity of SPICA at FIR is to try to detect debris disks with large fractional excesses (relative to the stellar photospheres) at large distances, i.e. a volume limited debris disk survey. With a limited available observing time, higher detection rate is preferred. Early type stars (A and F types) are the most promising targets because they are associated with bright debris disks more frequently than other spectral type stars. Targeted observations of carefully selected A type stars within a few kpc will provide statistically uniform samples. This data set will dramatically increase bright debris disks around A type stars and enable us to study early phase of planetary system formation of early type stars statistically. Solar type stars (G type) are more important because they provide more direct information about formation process of our own solar system but bright debris disks are rarer than early type stars.

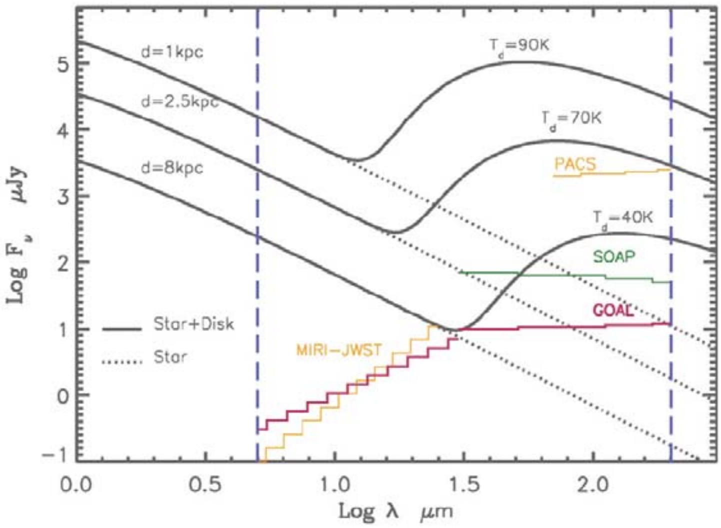

Fig.2.4-6 Spectral energy distributions of debris disks at distances 1, 2.5, and 8kpc compared with SPICA/SAFARI (SOAP & GOAL) sensitivity as well as JWST/MIRI and Herschel/PACS.

Objective #4: Role of Ice for Planet Formation

We will reveal the distribution and crystallinity of water ice in the disk, and investigate role of ice for planet formation, and how the elements for originating and sustaining life could be supplied to terrestrial protoplanets.

Water ice is supposed to play a significant role in the formation of planets. Below gas temperatures of ~150 K, water vapor freezes out and the main form of water in the cold disk midplane and at large disk radii will be ice which determines the position of the so called "*snow line*" (the water ice sublimation front; see figure). Grains covered by water icy mantles enable the formation of planetesimals and the core of gas giants beyond the snow line, which separates the inner disk region of terrestrial, rocky planets from that of the outer gas giant planets. Furthermore, it is possible that during the later phases of planetary formation, the atmospheres, and indeed the oceans, of the rocky planets are formed by bombardment of comets and asteroids which contain water ice. However, very little is known or constrained from observational point of view. It is partly because water ice grains have spectral features at ~44 μm and ~62 μm that are difficult to be accessed so far.

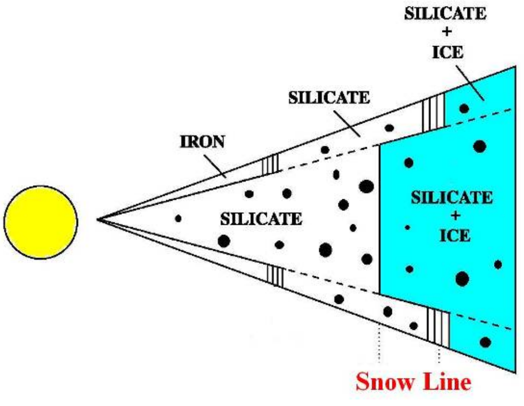

Fig.2.4-7 position of "snow line"

SPICA enables us to access various water ice features especially at ~44 μm (never accessed since

ISO) and ~62 μm. In particular 44 μm water ice feature is a powerful tool to investigate the crystallinity (crystal or amorphous) of water ice and its temperature. For most disk sources, it is impossible or very difficult to use MIR absorption features to trace water ice and the material is too cold to emit in the NIR/MIR bands. Hence, these strong FIR features are robust probes of (1) the presence/absence of water ice, even in cold or heavily obscured regions without a MIR background, and (2) the amorphous/crystalline state which provides clues on the formation history of water ice and origin of comets. Note that *JWST* can not access these solid state bands and *Herschel* only has access to the ~62 μm band with much poorer sensitivity and limited bandwidth. Therefore, ice spectroscopic survey with SPICA/SAFARI towards a broad range of environments (such as protostellar envelopes, circumstellar disks, and solar system bodies) enables us to explore the role of ice for planetary formation and evolution and the emergence of habitable planets. SPICA surveys will thus provide the first census of the water ice content towards hundreds of planet forming systems in our Galaxy. A complementary approach with SPICA/SCI to search for NIR ice absorption features in the disk scattered light spectra should be accomplished (see e.g., Honda et al. 2009 for water ice coronagraphic observations at ~3.1 μm).

For nearby debris disks (d~10 pc) such as those around Vega, Formalhaut or β Pictoris (~100 A-type stars), the angular resolution of SPICA at the 44 μm water ice feature will be sufficient *to spatially resolve the location of the snow line* (the diffraction limited resolution is ~3") . In debris disk, presence of water ice grain is not fully established. There is a prediction that water ice grains can not survive around early type stars due to photosputtering by UV irradiation (Grigorieva et al. 2007). Therefore, observation of presence/absence of water ice grains around debris disks and its distribution is important to understand the stability of ice grains. Furthermore, SPICA/SCI MIR coronographic spectroscopic studies of disk scattered light should also be made because it enables us high angular resolution spectro-imaging, which is complementary to SPICA/SAFARI observations, again. SCI high contrast and spectroscopic capabilities will enable to detect MIR dust/ice spectral features in very faint debris disk and investigate their evolution as a function of disk radii.

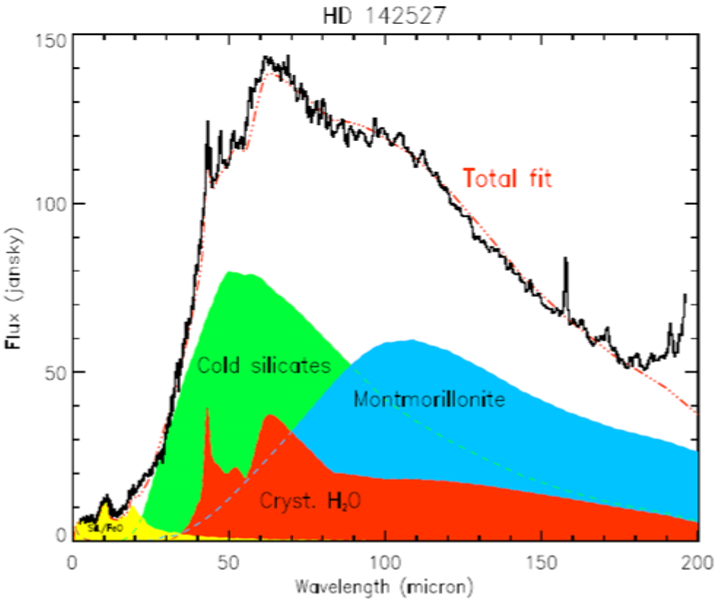

Fig.2.4-8 ISO spectrum of the circumstellar disk around HD 142527 young star (adapted from Malfait et al. 1999) showing the model components including the crystalline water ice FIR features. Water ice can only be directly detected at these temperatures through the ~44 and ~62µm FIR emission features. SPICA will take the equivalent spectra of objects at flux levels less than 10 mJy in one minute in SAFARI's low spectral resolution mode.

Objective #5: Survey of Primordial Objects in the Solar System

In order to reveal the whole picture of the solar system, we will survey physical information on primordial objects in the solar system.

Since the discovery of the first Kuiper-Belt object, 1992 QB1 (Jewitt & Luu 1993), our view of the solar system is undergoing radical changes and has been expanding. One of the goals for the solar system science in the next decades is the establishment of comprehensive catalogue of physicochemical properties for primitive solar system small bodies (SSSBs); near-Earth objects, main-belt asteroids, Jovian Trojans, Centaurs, trans-Neptunian objects (TNOs), comets, and so on. Albedos, diameters, and thermal inertias of SSSBs from asteroids to TNOs are particularly important information for the study on the origin and evolution of the solar system. It is generally recognized that TNOs are the remnants of planetesimals beyond Neptune's orbit in the early solar nebula, which are physicochemically unaltered by the solar radiation. The present distribution of TNOs shows the sign of the dynamical migration of the giant planets in the early solar nebula (Malhotra 1993; Levison & Morbidelli 2003). It is a hint of the initial mass distribution of the planetesimals in the proto-planetary nebula (Morbidelli et al. 2003; Gomes et al. 2005).

It is, however, not easy to derive the albedo and size of TNOs by observations in either optical (reflected light) or infrared/radio (thermal emission) range alone. The combination of measurements at optical and infrared/radio range constrain these properties of TNOs. Especially, multi-band observations of the thermal emission around its peak wavelength are important for the determination of the precise SED of TNOs (Stansberry et al. 2008; Brocker et al. 2009). SPICA/SAFARI-MIRMES will cover the wavelength region of thermal radiation of asteroids and TNOs (30 to 210 μm) and have good sensitivity throughout the infrared. It is also supposed that surface conditions of TNOs might give us information on the constituent materials that make up planetesimals. In the far-infrared region, there are diagnostic spectral features of water ice and minerals. Past infrared satellites, and even Herschel, do not have the enough capabilities and sensitivities to detect these features in far-infrared region. SPICA/SAFARI will be the first instrument to observe these ice and dust features for the brightest TNOs.

SPICA/SAFARI will be able to detect most of the known outer SSSBs and the SSSBs which will be discovered in the future in the photometric mode, specifically TNOs of 50 km in diameter at 35 AU, and 100 km TNOs at 50 AU (Fig.2.4-9). Herschel will observe the TNOs larger than 250 km, and requires ~300 hours to detect photometrically ~10% of the currently known TNOs. JWST does not cover the critical wavelength range longer than 30 micron. In addition, SPICA/SAFARI can carry out the first far-infrared spectral survey for the brightest TNOs. Therefore, SPICA will provide the precious information to the correlation between the size and albedo distribution and the orbital properties for TNOs, and clarify the dynamical evolution beyond the giant planet region in the early solar nebula. With the help of 10 times or more higher sensitivity than AKARI, we will make an unprecedented survey of the albedo, size, thermal inertia, and surface condition for SSSBs. Since the confusion limit does not apply for moving objects like TNOs, extremely deep sensitivity (better than 50μJy, 5σ, achieved with SAFARI GOAL detectors) in the far-IR can provide dramatic improvement in the exploring capability of our solar system, hence highly recommended.

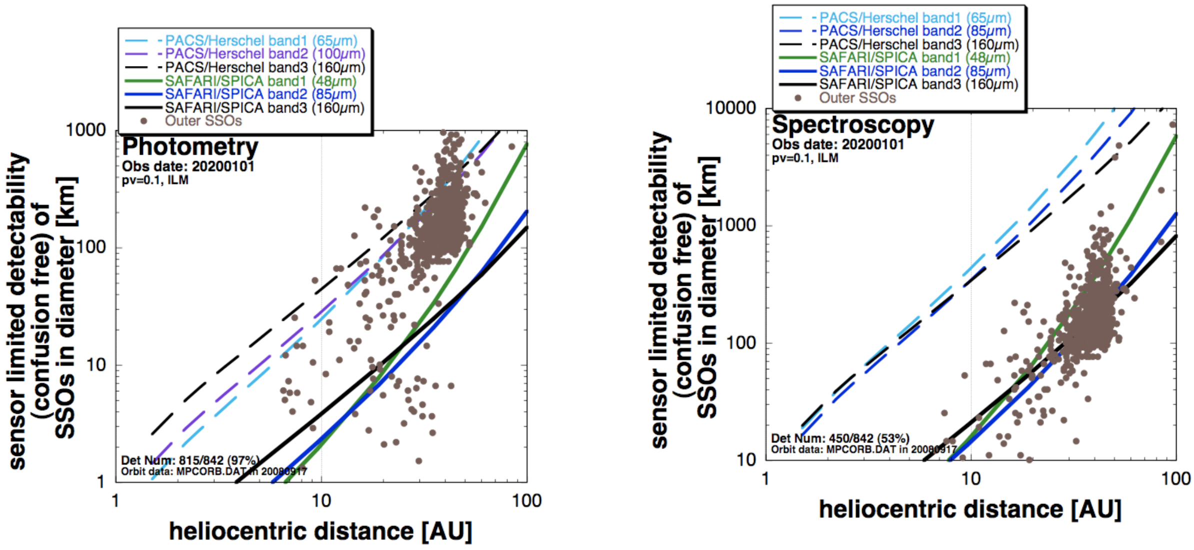

Fig. 2.4-9 Diameters (in km) of a pop

ulation of known outer solar system objects as a function of their heliocentric distance, compared with the detectability predictions for photometry (left) and spectroscopy (right). SAFARI predictions do not take into account the confusion limits.

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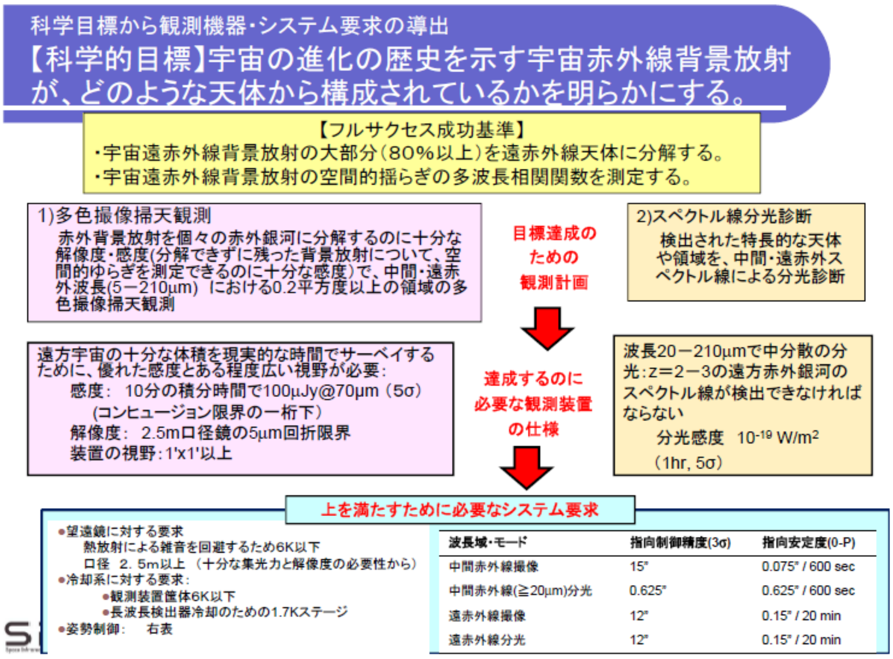
3. ミッション要求 Mission Requirements

3.1 科学目標・成功基準からミッション要求の導出 Mission Requirement Breakdown from Scientific Targets and Success Cliteria

2章で述べた科学目標とフルサクセス成功基準からミッション要求が導かれる過程を図3.1-1～3に示す。



科学目標から観測機器・システム要求の導出

【科学的目標】宇宙の進化の歴史を示す宇宙赤外線背景放射が、どのような天体から構成されているかを明らかにする。

【フルサクセス成功基準】
・宇宙遠赤外線背景放射の大部分（80％以上）を遠赤外線天体に分解する。
・宇宙遠赤外線背景放射の空間的揺らぎの多波長相関関数を測定する。

1)多色撮像掃天観測
赤外背景放射を個々の赤外銀河に分解するのに十分な解像度・感度(分解できずに残った背景放射について、空間的ゆらぎを測定できるのに十分な感度)で、中間・遠赤外波長(5－210μm) における0.2平方度以上の領域の多色撮像掃天観測

2)スペクトル線分光診断
検出された特長的な天体や領域を、中間・遠赤外スペクトル線による分光診断

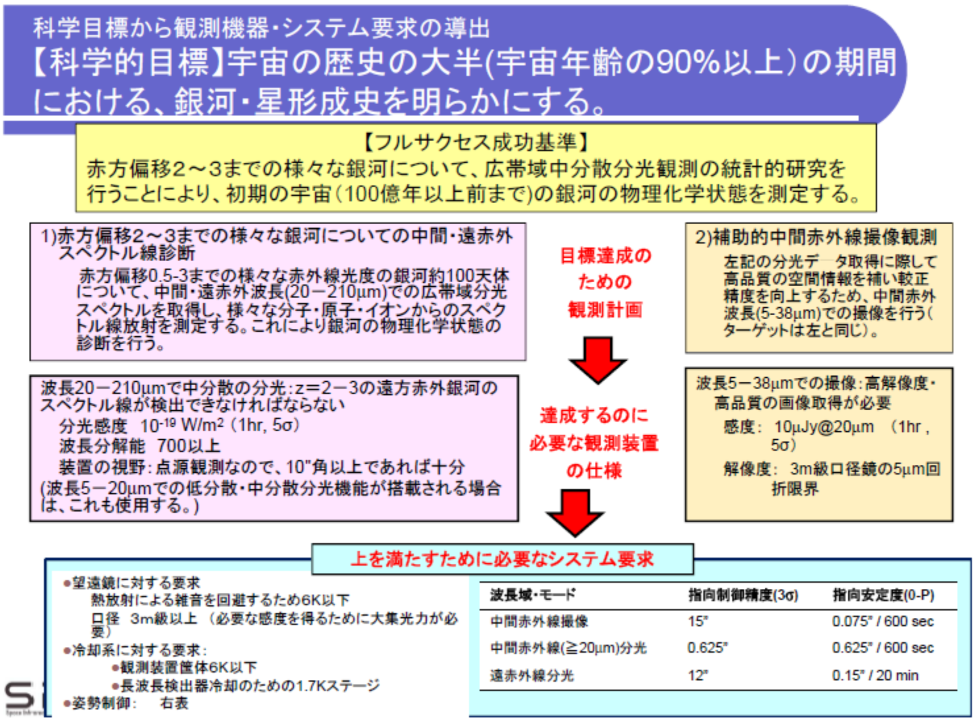
遠方宇宙の十分な体積を現実的な時間でサーベイするために、優れた感度とある程度広い視野が必要：
感度： 10分の積分時間で100μJy@70μm（5σ）
(コンヒュージョン限界の一桁下）
解像度： 2.5m口径鏡の5μm回折限界
装置の視野：1'x1'以上

波長20－210μmで中分散の分光：z＝2－3の遠方赤外銀河のスペクトル線が検出できなければならない
分光感度 10^{-19} W/m^2
（1hr, 5σ）

上を満たすために必要なシステム要求

- 望遠鏡に対する要求
  熱放射による雑音を回避するため6K以下
  口径 2. 5m以上 （十分な集光力と解像度の必要性から）
- 冷却系に対する要求：
  - 観測装置筐体6K以下
  - 長波長検出器冷却のための1.7Kステージ
- 姿勢制御： 右表

波長域・モード	指向制御精度(3σ)	指向安定度(0-P)
中間赤外線撮像	15"	0.075" / 600 sec
中間赤外線(≧20μm)分光	0.625"	0.625" / 600 sec
遠赤外線撮像	12"	0.15" / 20 min
遠赤外線分光	12"	0.15" / 20 min



科学目標から観測機器・システム要求の導出

【科学的目標】宇宙の歴史の大半(宇宙年齢の90％以上）の期間における、銀河・星形成史を明らかにする。

【フルサクセス成功基準】
赤方偏移2～3までの様々な銀河について、広帯域中分散分光観測の統計的研究を行うことにより、初期の宇宙（100億年以上前まで)の銀河の物理化学状態を測定する。

1)赤方偏移2～3までの様々な銀河についての中間・遠赤外スペクトル線診断
赤方偏移0.5-3までの様々な赤外線光度の銀河約100天体について、中間・遠赤外波長(20－210μm)での広帯域分光スペクトルを取得し、様々な分子・原子・イオンからのスペクトル線放射を測定する。これにより銀河の物理化学状態の診断を行う。

2)補助的中間赤外線撮像観測
左記の分光デ－タ取得に際して高品質の空間情報を補い較正精度を向上するため、中間赤外波長(5-38μm)での撮像を行う(ターゲットは左と同じ)。

波長20－210μmで中分散の分光：z＝2－3の遠方赤外銀河のスペクトル線が検出できなければならない
分光感度 10^{-19} W/m^2（1hr, 5σ）
波長分解能 700以上
装置の視野：点源観測なので、10"角以上であれば十分
(波長5－20μmでの低分散・中分散分光機能が搭載される場合は、これも使用する。)

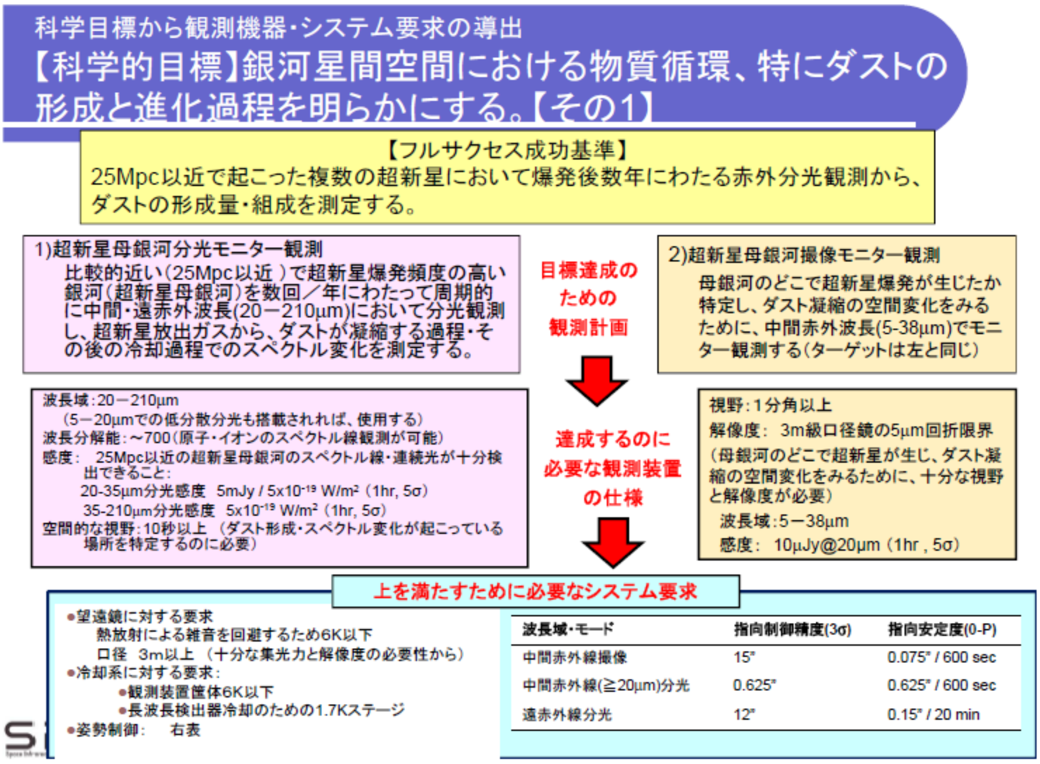
波長5－38μmでの撮像：高解像度・高品質の画像取得が必要
感度： 10μJy@20μm （1hr , 5σ）
解像度： 3m級口径鏡の5μm回折限界

上を満たすために必要なシステム要求

- 望遠鏡に対する要求
  熱放射による雑音を回避するため6K以下
  口径 3m級以上 （必要な感度を得るために大集光力が必要）
- 冷却系に対する要求：
  - 観測装置筐体6K以下
  - 長波長検出器冷却のための1.7Kステージ
- 姿勢制御： 右表

波長域・モード	指向制御精度(3σ)	指向安定度(0-P)
中間赤外線撮像	15"	0.075" / 600 sec
中間赤外線(≧20μm)分光	0.625"	0.625" / 600 sec
遠赤外線分光	12"	0.15" / 20 min

図 3.1-1 科学目標・フルサクセス成功基準からミッション要求が導かれる過程（銀河誕生のドラマ）



科学目標から観測機器・システム要求の導出

【科学的目標】銀河星間空間における物質循環、特にダストの形成と進化過程を明らかにする。【その1】

【フルサクセス成功基準】
25Mpc以近で起こった複数の超新星において爆発後数年にわたる赤外分光観測から、ダストの形成量・組成を測定する。

目標達成のための観測計画

1)超新星母銀河分光モニター観測
比較的近い(25Mpc以近)で超新星爆発頻度の高い銀河(超新星母銀河)を数回／年にわたって周期的に中間・遠赤外波長(20－210μm)において分光観測し、超新星放出ガスから、ダストが凝縮する過程・その後の冷却過程でのスペクトル変化を測定する。

2)超新星母銀河撮像モニター観測
母銀河のどこで超新星爆発が生じたか特定し、ダスト凝縮の空間変化をみるために、中間赤外波長(5-38μm)でモニター観測する(ターゲットは左と同じ)

達成するのに必要な観測装置の仕様

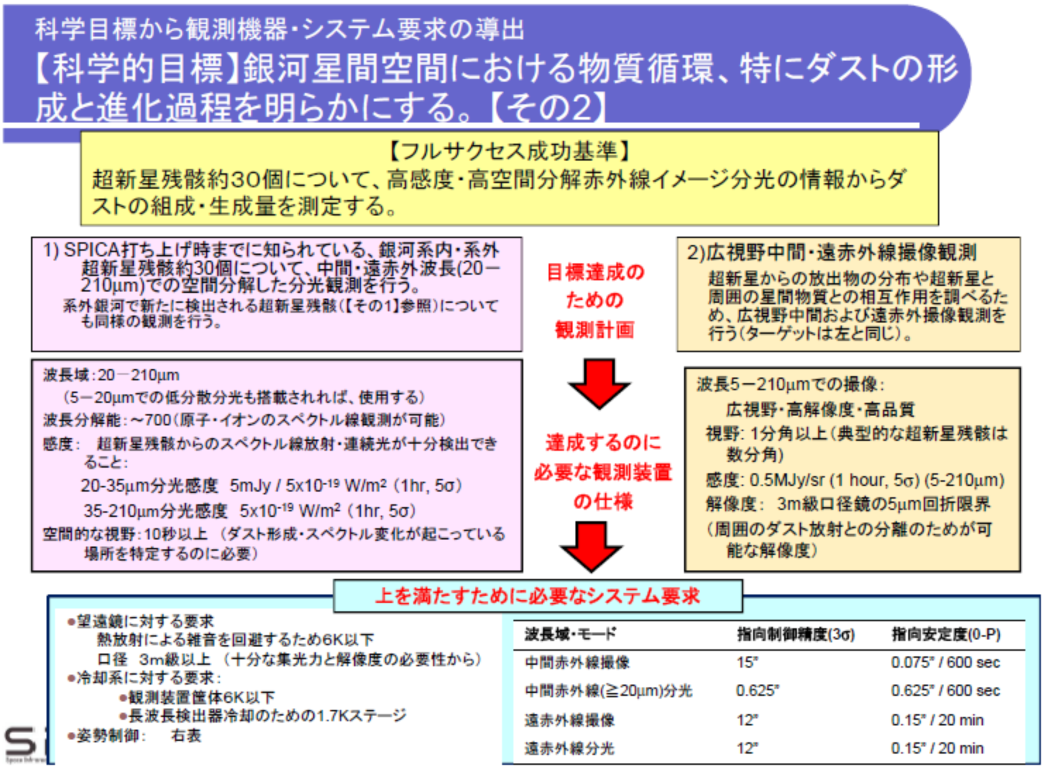
波長域:20－210μm
（5－20μmでの低分散分光も搭載されれば、使用する）
波長分解能:～700（原子・イオンのスペクトル線観測が可能）
感度:　25Mpc以近の超新星母銀河のスペクトル線・連続光が十分検出できること:
20-35μm分光感度　5mJy / 5x10^{-19} W/m^2（1hr, 5σ）
35-210μm分光感度　5x10^{-19} W/m^2（1hr, 5σ）
空間的な視野:10秒以上　（ダスト形成・スペクトル変化が起こっている場所を特定するのに必要）

視野:1分角以上
解像度:　3m級口径鏡の5μm回折限界
（母銀河のどこで超新星が生じ、ダスト凝縮の空間変化をみるために、十分な視野と解像度が必要）
波長域:5－38μm
感度:　10μJy@20μm（1hr , 5σ）

上を満たすために必要なシステム要求

- 望遠鏡に対する要求
  熱放射による雑音を回避するため6K以下
  口径　3m以上　（十分な集光力と解像度の必要性から）
- 冷却系に対する要求:
  - 観測装置筐体6K以下
  - 長波長検出器冷却のための1.7Kステージ
- 姿勢制御:　右表

波長域・モード	指向制御精度(3σ)	指向安定度(0-P)
中間赤外線撮像	15"	0.075" / 600 sec
中間赤外線(≧20μm)分光	0.625"	0.625" / 600 sec
遠赤外線分光	12"	0.15" / 20 min



科学目標から観測機器・システム要求の導出

【科学的目標】銀河星間空間における物質循環、特にダストの形成と進化過程を明らかにする。【その2】

【フルサクセス成功基準】
超新星残骸約30個について、高感度・高空間分解赤外線イメージ分光の情報からダストの組成・生成量を測定する。

目標達成のための観測計画

1) SPICA打ち上げ時までに知られている、銀河系内・系外超新星残骸約30個について、中間・遠赤外波長(20－210μm)での空間分解した分光観測を行う。
系外銀河で新たに検出される超新星残骸(【その1】参照)についても同様の観測を行う。

2)広視野中間・遠赤外線撮像観測
超新星からの放出物の分布や超新星と周囲の星間物質との相互作用を調べるため、広視野中間および遠赤外撮像観測を行う(ターゲットは左と同じ)。

達成するのに必要な観測装置の仕様

波長域:20－210μm
（5－20μmでの低分散分光も搭載されれば、使用する）
波長分解能:～700（原子・イオンのスペクトル線観測が可能）
感度:　超新星残骸からのスペクトル線放射・連続光が十分検出できること:
20-35μm分光感度　5mJy / 5x10^{-19} W/m^2（1hr, 5σ）
35-210μm分光感度　5x10^{-19} W/m^2（1hr, 5σ）
空間的な視野:10秒以上　（ダスト形成・スペクトル変化が起こっている場所を特定するのに必要）

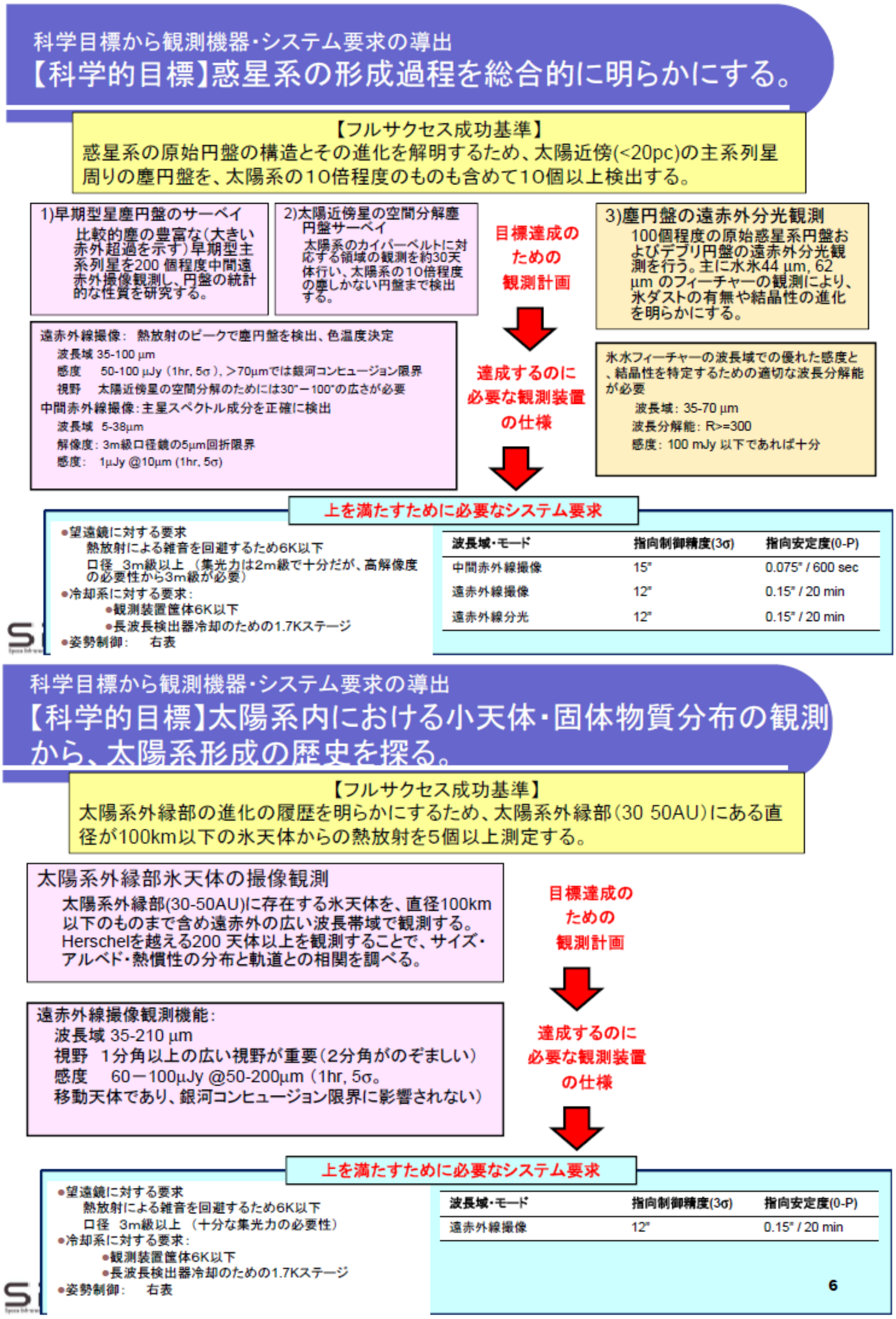
波長5－210μmでの撮像:
広視野・高解像度・高品質
視野: 1分角以上（典型的な超新星残骸は数分角）
感度: 0.5MJy/sr (1 hour, 5σ) (5-210μm)
解像度:　3m級口径鏡の5μm回折限界
（周囲のダスト放射との分離のためが可能な解像度）

上を満たすために必要なシステム要求

- 望遠鏡に対する要求
  熱放射による雑音を回避するため6K以下
  口径　3m級以上　（十分な集光力と解像度の必要性から）
- 冷却系に対する要求:
  - 観測装置筐体6K以下
  - 長波長検出器冷却のための1.7Kステージ
- 姿勢制御:　右表

波長域・モード	指向制御精度(3σ)	指向安定度(0-P)
中間赤外線撮像	15"	0.075" / 600 sec
中間赤外線(≧20μm)分光	0.625"	0.625" / 600 sec
遠赤外線撮像	12"	0.15" / 20 min
遠赤外線分光	12"	0.15" / 20 min

図 3.1-2 科学目標・フルサクセス成功基準からミッション要求が導かれる過程（物質輪廻の解明）



科学目標から観測機器・システム要求の導出

【科学的目標】惑星系の形成過程を総合的に明らかにする。

【フルサクセス成功基準】
惑星系の原始円盤の構造とその進化を解明するため、太陽近傍(<20pc)の主系列星周りの塵円盤を、太陽系の10倍程度のものも含めて10個以上検出する。

1)早期型星塵円盤のサーベイ
比較的塵の豊富な(大きい赤外超過を示す)早期型主系列星を200 個程度中間遠赤外撮像観測し、円盤の統計的な性質を研究する。

2)太陽近傍星の空間分解塵円盤サーベイ
太陽系のカイパーベルトに対応する領域の観測を約30天体行い、太陽系の10倍程度の塵しかない円盤まで検出する。

3)塵円盤の遠赤外分光観測
100個程度の原始惑星系円盤およびデブリ円盤の遠赤外分光観測を行う。主に水氷44 μm, 62 μm のフィーチャーの観測により、氷ダストの有無や結晶性の進化を明らかにする。

目標達成のための観測計画

遠赤外線撮像:　熱放射のピークで塵円盤を検出、色温度決定
波長域 35-100 μm
感度　50-100 μJy (1hr, 5σ), >70μmでは銀河コンヒュージョン限界
視野　太陽近傍星の空間分解のためには30"－100"の広さが必要
中間赤外線撮像: 主星スペクトル成分を正確に検出
波長域　5-38μm
解像度: 3m級口径鏡の5μm回折限界
感度:　1μJy @10μm (1hr, 5σ)

氷水フィーチャーの波長域での優れた感度と、結晶性を特定するための適切な波長分解能が必要
波長域: 35-70 μm
波長分解能: R>=300
感度: 100 mJy 以下であれば十分

達成するのに必要な観測装置の仕様

上を満たすために必要なシステム要求

- 望遠鏡に対する要求
  熱放射による雑音を回避するため6K以下
  口径　3m級以上 (集光力は2m級で十分だが、高解像度の必要性から3m級が必要)
- 冷却系に対する要求:
  - 観測装置筐体6K以下
  - 長波長検出器冷却のための1.7Kステージ
- 姿勢制御:　右表

波長域・モード	指向制御精度(3σ)	指向安定度(0-P)
中間赤外線撮像	15"	0.075" / 600 sec
遠赤外線撮像	12"	0.15" / 20 min
遠赤外線分光	12"	0.15" / 20 min

科学目標から観測機器・システム要求の導出

【科学的目標】太陽系内における小天体・固体物質分布の観測から、太陽系形成の歴史を探る。

【フルサクセス成功基準】
太陽系外縁部の進化の履歴を明らかにするため、太陽系外縁部(30 50AU)にある直径が100km以下の氷天体からの熱放射を5個以上測定する。

太陽系外縁部氷天体の撮像観測
太陽系外縁部(30-50AU)に存在する氷天体を、直径100km以下のものまで含め遠赤外の広い波長帯域で観測する。Herschelを越える200 天体以上を観測することで、サイズ・アルベド・熱慣性の分布と軌道との相関を調べる。

目標達成のための観測計画

遠赤外線撮像観測機能:
波長域 35-210 μm
視野　1分角以上の広い視野が重要(2分角がのぞましい)
感度　60－100μJy @50-200μm (1hr, 5σ。
移動天体であり、銀河コンヒュージョン限界に影響されない)

達成するのに必要な観測装置の仕様

上を満たすために必要なシステム要求

- 望遠鏡に対する要求
  熱放射による雑音を回避するため6K以下
  口径　3m級以上 (十分な集光力の必要性)
- 冷却系に対する要求:
  - 観測装置筐体6K以下
  - 長波長検出器冷却のための1.7Kステージ
- 姿勢制御:　右表

波長域・モード	指向制御精度(3σ)	指向安定度(0-P)
遠赤外線撮像	12"	0.15" / 20 min

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図 3.1-3 科学目標・フルサクセス成功基準からミッション要求が導かれる過程（惑星系のレシピ）

3.2 ミッション要求サマリ Summary of Mission Requirements

ミッション要求は、目標を達成するために必要な要求事項を集約したものである。要求は仕様とは区別され、機能要求として記述する。ただし、観測機器等については技術的な性能要求(「仕様」

とは異なる)についても記述する。

The mission requirements describes the required instrumental capability to achieve the scientific objectives & targets. Note that the ``Requirements” is different from the ``Specifications”, and they are described as functional requirements over variety of technical aspects.

前節で示したブレークダウンから、フルサクセスレベル（2.1 節）で達成するために必要かつ十分なミッション要求を以下のようにまとめた：

- **望遠鏡に対する要求**
    - 口径３mクラスの望遠鏡を極低温（６K以下）に冷却
    - 精度：波長 5μm での回折限界、波面誤差で 0.35μm 以下
    - 視野 30 分Φ以上
    - 光学効率変化：　ミッション期間中効率が 10%以上劣化しないこと
      （→ コンタミネーションに関するシステム要求）
- **コア波長：**　5－210μm
    - JWST、ALMA では観測できない波長帯
- **観測期間：**　２年以上
- **可視範囲：**全天の 20%以上の領域が観測できる visibility を有すること。
- **データ発生量：**　4 M bps　（一日分の観測データを蓄積し、地上に伝送できること）

- **焦点面観測装置**
    - 検出感度 ：Herschel（波長＞60μm）よりも 1.5 桁以上の分光感度、コンヒュージョン限界の撮像感度。
    - 視野要求：
      中間赤外線撮像：4 分角以上 ／　遠赤外線撮像：2 分角以上
    - 波長域・波長分解能要求：
      ５－２１０ μm （撮像)、２０－２１０μm で低分散・中分散分光機能
    - 姿勢精度要求

波長域・モード	指向制御精度(3σ)	指向安定度(0-P)
中間赤外線撮像	15”	0.075” / 600 sec
中間赤外線(≧20μm)分光	0.625”	0.625” / 600 sec
遠赤外線撮像	12”	0.15” / 20 min
遠赤外線分光	12”	0.15” / 20 min

次に FPI オプション機器・機能要求に関しては、以下のようにまとめられる：

- **オプション観測装置についての機能要求**

R~100 の低分散、及び 1000 の中分散分光機能（5-20μm）
R~30,000 の高分散分光機能（4-8, 12-18μm）
中間赤外コロナグラフ機能
サブミリ波分光機能
近赤外(0.8-5μm)分光・撮像機能

- **オプション観測装置についての姿勢精度要求**

波長域・モード	指向制御精度(3σ)	指向安定度(0-P)
中間赤外線高分散分光	0.135”	0.075” / 600 sec
中間赤外線コロナグラフ	0.03”	0.03” / 20 min

以上の要求根拠（特に、前節のブレークダウンでは明示していない観測期間・可視性・データ量、望遠鏡光学効率）については、3.3 節、3.4 節で詳しく述べる。

3.3 ミッション要求の詳細 Overview & Summary of Mission Requirements

表 3 にミッション要求の詳細を示した。以下にこれらの要求根拠および背景を詳細に述べる。

(ア) 波長領域 Wavelength Coverage

JWST・Herschel・ALMA では困難だが SPICA でこそ行うべき科学目的・目標を 2 章では詳しく述べた。これらを達成するためには、赤外線、特に中間・遠赤外線での高感度の観測を行なうことが最重要である。そこで、SPICA では、波長 5-210μm の中間・遠赤外線領域をコア波長域と設定する（それより短波長および長波長側はオプション)。JWST と Herschel のカバーしない波長域（20－60μm）では、SPICA のみが感度および解像度で独壇場となる。また、この波長 20μm―210μm をカバーすることがミッションの成功に必須である。

In section 2, we described the scientific objectives & targets which shall be performed uniquely with SPICA, while they are quite difficult to be achieved with JWST, Herschel, and ALMA. High sensitivity in the mid-and far-IR is most important. Therefore, the core wavelength of SPICA is defined as 5-210 μm, and shorter or longer wavelength extension is optional. Namely, wavelengths longer than 20μm, where JWST/MIRI lacks good capability, are mandatory to be covered with SPICA.

(イ) 望遠鏡の温度 Temperature of the Telescope

波長 5-210μm の中間・遠赤外線領域において、充分な感度を達成しようとする際に留意すべき点は、観測機器からの熱放射を、自然背景放射よりも低く抑えることである。これができないと、観測機器からの熱放射の揺らぎが観測限界を決めてしまうことになり、本来達成することができる感度にまで到達することができないためである。遠赤外線域で自然背景放射よりも、

望遠鏡の熱放射をおさえるためには、望遠鏡を 6 K 以下に冷却しなければならない（図 3.1-4）。A key requirement to achieve sufficient sensitivity at 5-210μm is to suppress the thermal emission from the instrumentation well below the natural background emission. As shown in Fig. 3.1-4, the telescope should be cooled to (or below) 6K to achieve the requirement.

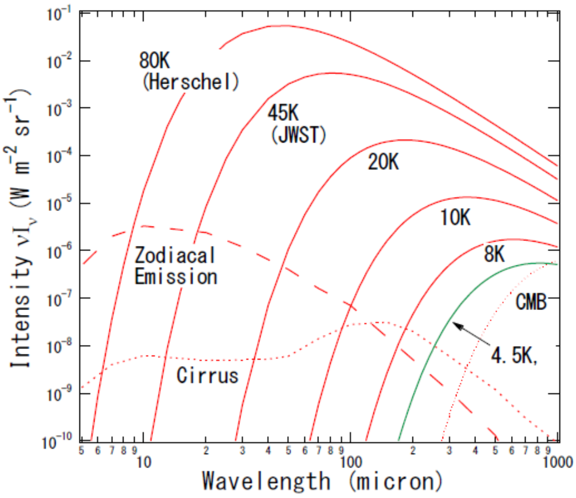


Fig. 3.1-4：Comparison between thermal emission from the telescope at various temperature and the natural background radiation (zodiacal emission and Cirrus(Galactic dust emission).

(ウ) 望遠鏡の口径 Diameter of the Telescope Primary Mirror

望遠鏡の口径に対する要求には、集光力と解像度という 2 つの側面がある。多くの科学目標の達成のためには 3.0m 級以上が必要である（2.5m 未満では、殆どの科学目標の達成が不可能である）。集光力は、天体の検出感度に直接影響する（(エ) で詳述)。解像度要求は、多くのミッション要求において、厳しいものはない（コロナグラフ観測は例外、以下に詳述)。60μm より長波長側では、Herschel の解像度を上回ることはできないが、我々の銀河系内の星間物質や近傍銀河の観測においては、Herschel には不可能な低輝度拡散放射を高精度で測定することが SPICA だけが可能であることを考えると、3m クラスの口径の実現が強く望まれる。

なお解像度要求は、3m 級口径の回折限界をすべてのコア波長域で実現すること、であるので、鏡面精度に対する要求となる。コロナグラフ観測に関してはさらに厳しい鏡面精度要求がある（3.2.3 に詳述)。

There are two aspects in the telescope diameter requirement, the light-collecting power and the spatial resolving power. In most of scientific targets, 3.0m-class or larger telescope is necessary. The light-collecting power directly affects the sensitivity, while the spatial resolving power requirement is not so stringent for most of the science requirements except for the coronagraph observations. Although Herschel achieved excellent spatial resolving power at wavelengths beyond 60μm, only SPICA enables us to accurately measure the faint diffuse emission from the interstellar matter and nearby galaxies with the cooled 3-m class telescope.

(エ) 感度 Sensitivity

ミッション要求の実現のためには、以下の感度を一時間程度の積分時間（5σ）で達成することが求

められる。これらを達成するには、FPI の性能も重要だが、望遠鏡の口径（集光力）を約 3m 以上とすることが必要である。

It is desired to achieve the following sensitivities in one hour integration (5σ) or so with sufficiently high performance of FPI as well as the collecting power of 3m-class telescope.

中間赤外線撮像 MIR imaging（**波長** 5ー40μm）: 10μJy at least, 1μJy is favorable

遠赤外線撮像 FIR imaging（**波長** 40ー200 μm）: 100μJy @50μm at least, 50μJy is favorable

（excluding the confusion limit **コンヒュージョン限界は除外した数値**）

中間赤外線分光 MIR spectroscopy（**波長** 5ー40μm）:

（**低分散** low-dispersion） 50μJy at least, 10μJy is favorable

（**中分散** moderate-dispersion） Line sensitivity: 10^{-19}W/m^2 at least

遠赤外線分光 FIR spectroscopy（**波長** 40ー210 μm）:

（**低分散** low-dispersion） 1mJy @50 μm at least, 0.2mJy is favorable

（**中分散** moderate-dispersion） Line sensitivity: 10^{-18}W/m^2 at least

（検出器のピクセルサイズを最適化できるのであれば）望遠鏡の集光力と、天体の検出限界は反比例する。 従って 3.0m の場合、3.5m の時の検出限界は 1/0.73=1.4 倍に悪化する。次に述べるコンヒュージョン限界と無関係な撮像・分光観測では、観測時間（検出限界の 2 乗に比例して増大）が、ほぼ 3.5m の場合の 2 倍必要となる。

The detection limit for a point-like source is inversely proportional to the light-collecting power of the telescope (so far as the detector pixel size, i.e. spatial sampling resolution is optimized. Thus, the detection limit with 3.0m aperture is worse by a factor of 1/0.73=1.4 than that with 3.5m aperture. In case of observations free from the source confusion, roughly twice longer integration time (i.e. proportional to the square of the detection limit) is necessary for the 3.0m aperture telescope.

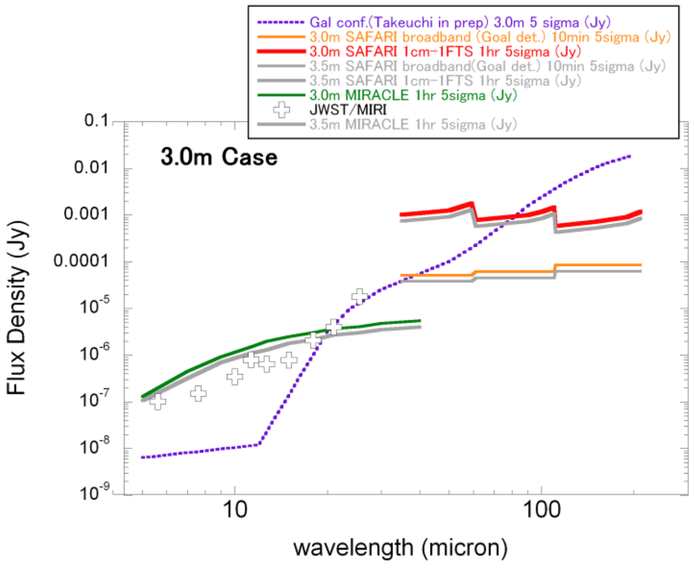


Fig.3.1-5 Expected point-source sensitivities of SPICA/MIRACLE (green) & SAFARI(red, orange) in case of 3.0m (effective diameter) telescope. Gray lines are for 3.5m telescope. Confusion limit by faint galaxies (Takeuchi et al. in prep.) is shown by dotted lines. Crosses are JWST/MIRI expected sensitivities.

(オ) 波長分解能 Wavelength Resolution

分光観測における波長分解能要求は以下となる。中間赤外では、JWST の分光機能にはない高分散分光機能を持つことが強く望まれる。

中間赤外線分光 MIR spectroscopy（**波長** 5ー40μm）:

（低分散 low-dispersion） $\lambda/\delta\lambda \sim 100$

（中分散 moderate dispersion） $\lambda/\delta\lambda \sim 1000$

（高分散 high dispersion、$\lambda<20$μm） $\lambda/\delta\lambda \sim 30{,}000$ (velocity resolution of 10km/s)

遠赤外線分光 FIR spectroscopy（**波長** 40ー210 μm）:

（低分散） $\lambda/\delta\lambda \sim 100$

（中分散） $\lambda/\delta\lambda \sim 2000$ at 100μm

(カ) 視野要求 Field-of-View

撮像・分光観測における視野要求は以下となる。中間赤外線では、JWST よりも十分大きな視野を持ち、掃天観測能力で JWST を圧倒すべきである。遠赤外線においては、低分散分光を行いつつ広い視野を観測する（３次元マッピング）能力をぜひ持つべきである。そのためには、各焦点面観測装置が、以下に掲げる視野を持つ必要がある。さらに、それらの観測装置を搭載するために、望遠鏡のケラレのない視野として、直径 30’φ以上が必要となる。

Field-of-view (FoV) requirements in both imaging and spectroscopy is shown below. In Mid-IR, sufficiently large FoV than JWST is desired. In the Far-IR, large imaging FoV with low-dispersion spectroscopic capability (i.e. 3D mapping) is recommended. Hence each instrument is required to have a FoV listed below. To accommodate the instruments, 30arccmin diameter unvignetted FoV of the telescope is required.

中間赤外線撮像 Mid-IR Imaging (5ー40μm) : 5’x5’ minimum, 6’x6’ is favorable

遠赤外線撮像 Far-IR Imaging (40ー200 μm): 2’x2’ minimum @40-70 μm deep imaging

中間赤外線分光 Mid-IR spectroscopy (5ー40μm):

>1’ desirable for low-resolution spectroscopy with multi-slit

>10” desirable for moderate-resolution spectroscopy

遠赤外線分光 Far-IR spectroscopy (40ー210 μm): 2’x2’ is desirable for fast 3D mapping

(キ) 観測期間 Duration of Observations

観測期間（定常運用に移行後、フルサクセスレベルの観測運用を終了するまでの期間）に対する要求は、観測ターゲットの可視性に大きく依存する。天の黄極方向を除き、SPICA が同じ天体を常に観測できるわけではなく、例えば黄道面方向の天体は、年に２か月程度の期間しか可視性がない。また天体によっては（超新星のように）定期的に観測を継続的に行う必要がある。このような理由から、観測期間は２年以上と要求されている。

The duration of observations (defined as a duration between the start and end of routine observation to achieve the objectives at the full-success level) critically depends on the visibility of the observation targets. Except for the objects near the ecliptic poles, SPICA cannot observe the same targets at any time. For example, the targets at the ecliptic plane will be visible over ~2 months from SPICA in a year. For some sources like Supernavae, periodic observations should be performed. Therefore, observing duration more than two years are requested.

また、科学コミュニティが掲げる全１６項目の科学目標をフルサクセスレベルで達成するのに必要な実観測時間（天体からの赤外線を実際に SPICA の装置で観測を行っている時間）は、口径 3.5m を前提とした場合 10－20 日、口径 3.0m の場合 20－40 日と見積もられている。表２, ３には合計 16 の科学目標を掲げており、これらの実行には実観測時間で約１年（口径 3.5m）、２年（口径 3.0m）が必要となる。衛星ミッションとしての成功基準 6 項目（表 2.1-2）すべてを満足するには、実観測時間で約９カ月が最低限必要である（口径 2.5m では、ミッション成功基準を達成するためだけの観測を行ったとしても、観測期間のマージンが殆ど確保できない)。

The net observing time (i.e. on-source exposure time with SPICA) to achieve the full-success level of each scientific target (in Table 2) is estimated to be 10-15 days in case of 3.5m telescope, while 20-30 days in case of 3.0m. To fulfill all the scientific targets in Table 2 (17 in total), the total net observing time amounts to approx. 1 year (2 year) for 3.5m (3.0m) telescope. In order to perform the Mission Success Cliteria(Table 2.1-2) at the Full-Success level, net observing time of at least 9 months is required. Hence with 2.5m aperture telescope, we cannot allocate margin in the nominal observing duration of two years.

(ク) 可視範囲 Visibility

上記に述べられたような限られた観測期間を有効に活用するために、観測期間中はいつでも、全天の 20%以上の領域が観測できる visibility を有すること。

To make the best use of the observation period discussed above, SPICA is required to have a visibility to cover more than 20% of the all sky at any time during the observation period.

(ケ) 運用(時期) Timing of Commissioning of the Mission

遠赤外・サブミリ波においては、Herschel が 2009 年に打ち上げられ、この波長域でこれまでになく高い解像度の観測がおこなわれる。この成果を十分に活かすこと、Herschel でできないことを見極めて SPICA による観測計画を立案すべきである。

また地上ではミリ波サブミリ波干渉計 ALMA が 2011 年頃から観測を開始する予定であるし、（主に近赤外線波長主体の）スペース大望遠鏡 JWST が 2014 年に打ち上げられる。SPICA は、これらの次世代観測装置と波長域や分光・撮像能力において相補的であり、従って未だ JWST・ALMA が運用を続けている間に観測を開始することが強く望まれる。

また地上光赤外の次期計画として提案されている大型望遠鏡 TMT が、やはり 2018 年頃の実現

を目指している。宇宙再電離期の天体の正体を探ること、惑星系形成の総合理解を進める上で、TMT と SPICA のシナジーは非常に重要であり、TMT と同時期の実現が望まれる。

Herschel has been launched in 2009, and undertaking far-infrared imaging with unprecedentedly high spatial resolving power. For planning the observation with SPICA we should take into account of the achievement of Herschel.

Atacama Large Millimeter/submillimeter Array (ALMA) will also start observations from around 2011, and JWST will be launched in 2014. SPICA is complimentary to these next generation facilities in respect of wavelength coverage and spectral/imaging capabilities, and thus early commissioning of SPICA is very much recommended.

Thirty Meter Telescope (TMT), a next generation telescope for the ground optical/IR astronomy, is also planned to start commissioning in 2018. In order to reveal the nature of sources responsible for the Cosmic re-ionization, and to thoroughly understand the planetary system formation, synergy between TMT and SPICA is quite important, and thus SPICA should be realized in the similar timing of TMT commissioning.

(コ) データ量 Data Volume and Rate

上記の視野を持つ観測機器を効率的に運用するためには、4Mbps 以上のデータ発生量に対して、それを一日分以上の観測データ蓄積し、地球に適切に伝送する能力を有することが求められる。

To operate the instruments with the FoV listed above, SPICA is required to be able to store the data for at least a day and send the data with the data rate of 4Mbps.

(サ) 望遠鏡の光学効率変化 effective transmittance of the telescope

上記で議論された感度をミッション中に維持するために、望遠鏡の光学効率がミッション期間中で 10%以上は変化しないよう、コンタミネーションが低く抑えられなければならない。

To keep the sensitivity during the mission, contamination of the telescope is required to keep low so that the effective transmittance of the telescope does not change more than 10% during the mission period.

(シ) 観測装置 Observing Instruments

2 章で述べた 3 つの科学目的大項目のすべてに用いられている観測装置は、MIRACLE、MIRMES、SAFARI の 3 つである。MIRHES は、「惑星系形成」の科学目標（表 2 および表 3 の第 1、第 2、第 3）と、「物質輪廻」の科学目標（第 3）の達成のために用いられている。

SCI、BLISS は、それぞれ「惑星系形成」（第 1、第 4）、「銀河進化」（第 1、第 2、第 3）のエクストラな成功基準達成のために用いられている。FPC-S も「銀河進化」（第 1、第 2）及び「物質輪廻」の第 4、6 目標のエクストラな成功基準を達成するために必要である。

Three focal plane instruments, MIRACLE, MIRMES, SAFARI, are utilized to perform all major scientific objectives. MIRHES is utilized to perform objectives in the planetary system formation (#1, #2, & #3) and the life cycle of interstellar matter (#3). SCI is utilized to perform the extra success of the planetary system formation (#1, #4), while BLISS is utilized to perform the extra success of the evolution of galaxies (#1, #2, & #3). FPC-S is also necessary to perform the extra success of the evolution of galaxies (#1 & #2) and the life-cycle of interstellar matter(#4, & #6).

(ス) 指向精度および安定度 Pointing accuracy and stability

ミッション要求から各観測モード毎に整理された観測指向精度要求および運用要求を本節にまとめる。精度要求は各々クロススリット方向とアロングスリット方向で異なり、要求異方性を持つ。以下、特に断りのない限り、より厳しいクロススリット方向の数値を示す。また N/A とは、その FPI の該当するモードにおいて非適用(Not Applicable)であることを示す。TBD 項目は具体的な数値が確定していないが、基本的に AKARI と同等性能を要求されることを前提とする。

The pointing accuracy and stability requirements for each observing mode are summarized as follows. The accuracy requirements is different between cross and along the slit directions. In the following values refer to those for the along-the-slit direction (more stringent).

ポインティングモードにおける指向精度要求 Pointing Mode

各観測モードのポインティングモードにおいて要求される指向精度要求を表 3.1-1 に示す。これらの要求に対して、単一周波数から構成される指向誤差を想定し周波数に応じた指向精度要求を表現したものを図 3.1-6 に示す。もっとも厳しい要求を赤太字で示す。

表 3.1-1 ポインティングモード指向精度要求

Table 3.1-1 accuracy/stability requirements in the pointing mode

Observation mode	Absolute pointing control accuracy [arcsec] (3σ)	Pointing stability [arcsec, 0-P] /time (3σ)
MIRACLE Imaging Short	15	0.075 / 600[sec]
MIRACLE Imaging Long	15	0.21 / 600[sec]
MIRACLE Spectroscopic Short	0.135	0.135 / 600[sec]
MIRACLE Spectroscopic Long	0.405	0.405 / 600[sec]
MIRHES (S-mode) 0.72 ” x3.5 ”	0.216	0.216 / 600[sec]
MIRHES (L-mode) 1.2 ” x6.0 ”	0.36	0.36 / 600[sec]
MIRMES (Arm-Short) 12 ” x6 ”	0.3	0.3 / 600[sec]
MIRMES (Arm-Long) 12 ” x12.5 ”	0.625	0.625 / 600[sec]
SAFARI (SPECObserve Mode)	12	0.15 / 20[min]
SAFARI (PHTObserve Mode)	12	0.15 / 20[min]
FPC-S Imaging mode	0.3	0.1 / 600[sec]
BLISS dispersion	0.5	0.5 / 1[hour]
Coronagraph	0.03 (0-P)	0.03 / 20[min]

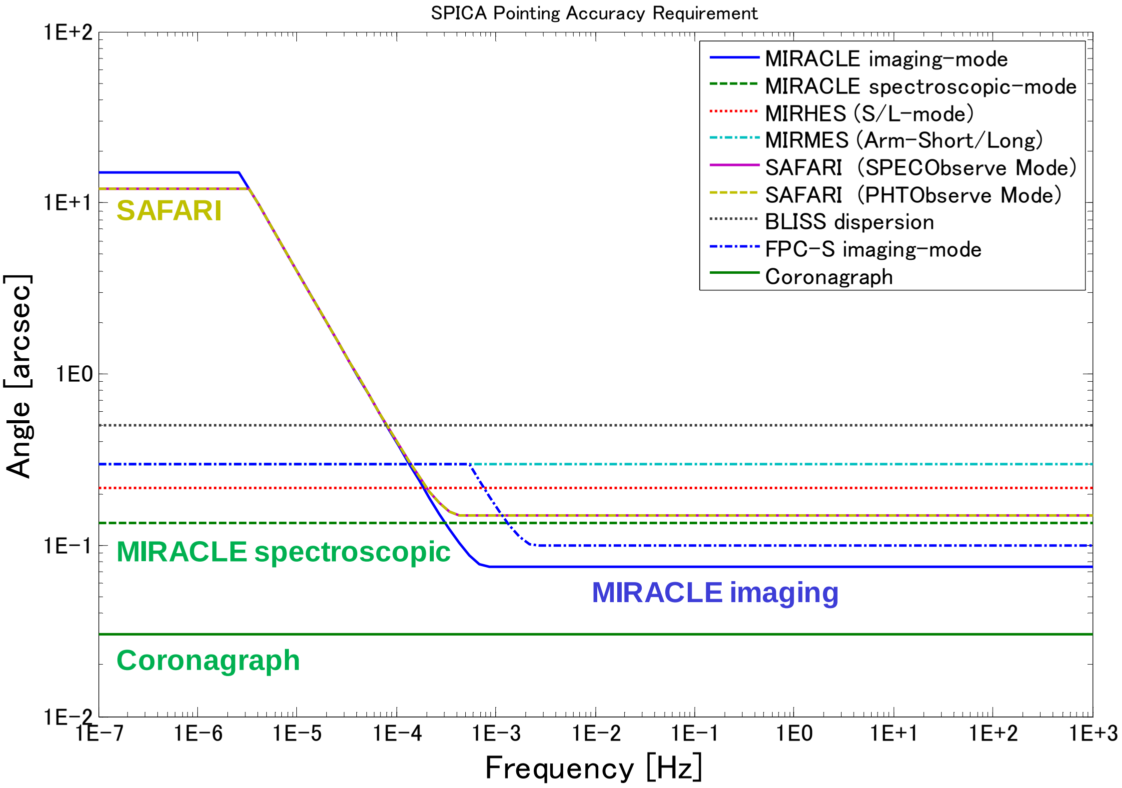


図 3.1-6 ポインティングモード指向精度要求（周波数領域表示）

Fig. 3.1-6 Pointing accuracy requirements in the frequency domain

指向決定精度要求　Attitude Determination Accuracy

ポインティングリコンストラクション後に達成すべき指向決定精度である。SAFARI、BLISS 等、陽に指向決定精度を要求する FPI を表に示す。他の FPI の決定精度は制御精度と同等レベルを達成要求とする（決定精度が制御精度より悪くなることは定義上ありえない）。

表 3.1-2 指向決定精度要求

Table 3.1-2 Attitude determination accuracy

Observation mode	Pointing determination accuracy [arcsec] (3σ) (After pointing reconstruction)
SAFARI	0.15
BLISS	0.5

ステップスキャンモードにおける指向精度要求　Step-scan mode

各観測モードにおけるステップ運用モードに対する指向精度要求を表に示す。ステップ方向は、衛星機体 X 軸回り／Y 軸回りあるいはその合成軸回りであり、Z 軸回りのステップ運用は、冷却系が要求する太陽角制限に基づき実施しないことを基本とする。

Requirements in the step-scan mode are shown in Table 3.1-3. Direction of a step is around X or Y-axis, or mixture of both axis of the spacecraft, while no step-scan around the Z-axis is permitted due to the Sun-avoidance angle constraint.

表 3.1-3 ステップスキャンモード指向精度要求
Table 3.1.3 Requirements in the step-scan mode

Observation mode	Step angle [arcsec]	Step angle accuracy[arcsec]	Settling time [sec]
MIRACLE Imaging dithering	0.075~22.8	0.075~0.39	30
MIRACLE Spectroscopic Step Scanning	0.135~1.14	0.135~0.57	30
MIRHES (S-mode) Single Staring	1.17 (along slit)	0.216	AKARI Performance Level
MIRHES (L-mode) Single Staring	2.0 (along slit)	0.36	AKARI Performance Level
MIRHES (S-mode) Step Mapping	0.36 or 0.72 (cross slit) 2.9 (along slit)	0.216	AKARI Performance Level
MIRHES (L-mode) Step Mapping	0.60 or 1.20 (cross slit) 5.0 (along slit)	0.36	AKARI Performance Level
MIRMES (Arm-Short) Single Staring	0.60 (cross slit) 6 (along slit)	0.3	AKARI Performance Level
MIRMES (Arm-Long) Single Staring	1.25 (cross slit) 6 (along slit)	0.625	AKARI Performance Level
MIRMES (Arm-Short) Step-Mapping	4.8 (cross slit) 10 (along slit)	0.3	AKARI Performance Level
MIRMES (Arm-Long) Step-Mapping	10 (cross slit) 10 (along slit)	0.625	AKARI Performance Level
FPC-S Step scan mode	3	0.1 (3σ)	N/A
SAFARI （SPECObserve Mode）	108	±12 (overlap)	100
SAFARI（PHTObserve Mode）	108	±12 (overlap)	100
BLISS	N/A	N/A	N/A
Coronagraph	N/A	N/A	N/A

彗星追尾モードにおける指向精度要求 Non-siderial tracking mode

各観測モードにおける彗星追尾モードに対する指向精度要求を表 3.1-4 に示す。彗星追尾モードを有しない観測モードを除き、基本的に指向精度要求はポインティングモードにおける指向精度要求と同等である。コロナグラフ観測装置の同モードは現状 N/A である。

表 3.1-4 彗星追尾モードにおける指向精度要求
Table 3.1.4 Requirements in the Non-siderial tracking mode

Items	Requirement
Pointing accuracy / stability	Same accuracy / stability as pointing mode
Tracking speed	< 10 arcsec/min
Tracking duration	< 1200 sec

スロースキャンモードにおける指向精度要求 Slow-scan mode

各観測モードにおけるスロースキャンに対する指向精度要求を表 3.1-5 に示す。スキャン速度×スキャン継続時間が FPC-G の視野範囲を超える場合には別途性能を規定する。SAFARI に関しては、FPC-G は本モードで用いないことを前提とする。

表 3.1-5 スロースキャンモード指向精度要求

Table 3.1-5 Slow-scan mode requirements

Observation mode	Scan speed range [arcsec/sec]	Scan speed accuracy [arcsec/sec]	Scan duration [sec]
MIRACLE Spectroscopic Slow scan	0.054~2.28	10 %	>5~50
MIRHES (S-mode)	N/A	N/A	N/A
MIRHES (L-mode)	N/A	N/A	N/A
MIRMES	N/A	N/A	N/A
FPC-S Slow scan mode	TBD	TBD	TBD
SAFARI （SPECObserve Mode）	N/A	N/A	N/A
SAFARI（PHTObserve Mode）	10~72	1%	600
BLISS (A2-D rastered mapping mode)	1~20	1% *1	600 *1
Coronagraph	N/A	N/A	N/A

*1 20arcsec/s で 10arcmin スキャン時

（参考：用語の定義）

指向精度　指向軸を観測対象方向に指向させる際の精度として定義する。具体的には、観測要求に応じて、絶対指向制御精度および指向安定度の規定がある。指向精度という場合には、これらの総称を表す概念として扱う。

絶対指向制御精度　観測対象を検出器の所定の位置に入れることを目的として、指向軸を観測対象方向に指向させる際の制御精度として、3σの統計量として定義する。指向制御精度は、搭載系で実現すべき精度である。指向制御精度には、その誤差要因として、アライメント誤差（あるいは、アライメント補正誤差)、姿勢制御誤差（あるいは指向軸制御誤差)、姿勢制御（あるいは指向軸制御）で制御できない内部擾乱による誤差を含む。

指向安定度　規定時間における検出器上の観測対象の移動量をある所定の値以下に抑えることを目的として、指向させるべき軸を観測対象方向に指向させる際の安定度として 3σの統計量として定義する。”0-P”は”P-P”の 2 分の 1 の意である。指向制御精度が時間的に一定である固定成分を含めて規定されるのに対して、指向安定度はこの成分を含まず、ある規定時間における変動成分のみで規定する。指向安定度は、搭載系で実現すべき精度である。指向安定度には、その誤差要因として、規定時間内に変動するアライメント安定度、姿勢制御安定度（あるいは指向軸制御安定度)、姿勢制御（あるいは指向軸制御）では制御できない内部擾乱誤差を含む。

3.4 科学目的別特記事項 Special topics for each Scientific Objectives

3.4.1. 銀河の誕生と進化過程の解明 Resolution of Birth and Evolution of Galaxies

望遠鏡口径：口径は、高赤方偏移宇宙の探査（目標第 1）にとって最も重要である。図 3.2-1 は、宇宙赤外線背景放射を、一個一個の銀河に分解する能力を、口径の関数として示したものである。宇宙赤外線背景放射の 50%を波長 160 で分解するためには、少なくとも 3m の口径が必要である。さらに、銀

河コンヒューージョンによる限界は、特に中間赤外線波長で口径に大きく依存する（図 3.2-2）。

The requirement on diameter of telescope is most serious for probing high-z universe (Objective #1). The best sensitivity is required for detecting distant, faint galaxies, hence the required observing time is inversely proportional to the effective collecting area of the telescope primary (common to all the objectives #1~#5). Figure 3.2-1 shows the capability of resolving CIRB as a function of telescope diameter. In order to resolve 50% of CIRB at 160μm, we need 3-m diameter at least. More importantly, however, the sensitivity limit due to the galaxy confusion is more stringent in the mid-infrared rather than far-infrared: showing strong dependence on the telescope diameter (Figure 3.2-2).

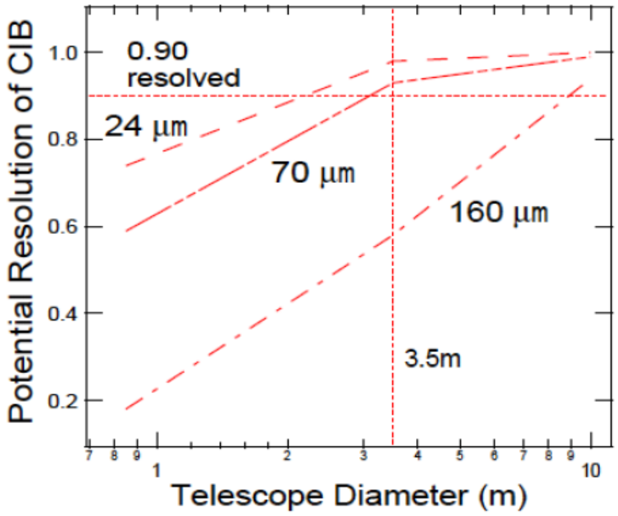


Fig. 3.2-1: Resolving capability of Cosmic Infrared Background (CIB) to discrete sources(galaxies) as a function of telescope diameter (Dole, 2004).

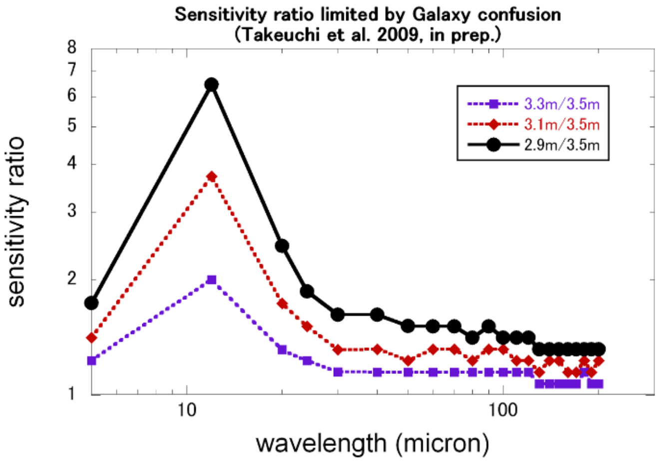


Fig. 3.2-2: sensitivity degradation factor (with respect to 3.5m) for the galaxy confusion limit (Takeuchi et al. in prep.).

波長域・検出感度・観測装置：　オプション装置の BLISS は、波長域・検出感度の面で SAFARI と相補的な装置であり、その実現は科学目標の達成のために強く望まれる。例えば、目標第 3 (Metallicity Evolution)で重要な役割を担う[C II] 158μm、[N II] 205μm 等のスペクトル線は、SAFARI では赤方偏移のために、我々が最も関心のある遠方宇宙の銀河からは観測することができない。

Wavelength Coverage / Sensitivity of BLISS (optional instrument) is complementary to those of SAFARI, and thus its realization is very much desired to achieve the extragalactic scientific targets. For example, the fine-structure lines such as [C II] 158μm, [N II] 205μm are known to play an important role to achieve the Objective #3 (Metallicity Evolution) from distant Universe cannot be observed with SAFARI due to the redshift.

3.4.2 銀河星間空間における物質輪廻の解明 The Transmigration of Dust in the Universe

観測装置の視野：近傍銀河や銀河系内星間塵雲の研究においては、天体は空間的に広がっており、波長によって変わらない固定された大きさの視野からの放射の、多波長分光スペクトル情報を取得することが強くのぞまれる。さらに、星などの点源のまわりのコンパクトな放射領域（～10数秒程度）の空間情報を得ることが非常に重要である。
観測期間要求：超新星観測（目標＃１）においては、最低１年にわたる時間的な変化を追うことが本質的である。このため、ミッション観測期間として２年以上継続することがのぞまれる。
望遠鏡口径：望遠鏡の口径縮小により観測限界が悪化することのサイエンスへの影響は、多くの科学目標に関して問題とならない（２m級でも実施可能なものもある)。しかし、遠赤外線波長域では口径３.５mの Herschel がすでに観測を開始していることを考えると、解像度を著しく落すことは避けなければならない。この点で３mクラスの実現が強く望まれる。

Field-of-View Requirement: in the study of interstellar matter of nearby galaxies and Galactic interstellar dust clouds, multi-wavelength spectra of the extended emission from the fixed-size FoV common to all the wavelength is strongly desired, in order to avoid the uncertainty from the spatial extension which may vary with wavelength. Furthermore, it is very important to obtain “compact” spatial information (~10 and a few arcsec scale) around the energy sources (such as stars).
Duration of Observation: as for the SNe observations (target #1), it is essential to follow the time variation. Thus it is strongly desired to have more than two years duration for the routine observation phase.
Diameter of Telescope: the impact of sensitivity degradation due to the shrink of the telescope diameter is moderate (even 2m-class, some mission objectives can be achieved), however, in the point of view of spatial resolving power, 3-m class aperture is highly recommended since Herschel Space Observatory (3.5m aperture) is already in space for far-IR and submm observations.

3.4.3 惑星系形成過程の総合理解 Thorough Understanding of Planetary System Formation

コロナグラフによる惑星探査：　この観測は、検出限界が鏡面反射率の一様性や表面精度に非常に大きく左右される。また、木星や土星と同様の軌道サイズの惑星系を探査するために、短い波長の観測が特に重要となる。ＪＷＳＴなどとの競合を考慮に入れると、他の観測装置やプロジェクトに比べ厳しい下記の仕様を達成する必要がある。

― 鏡面反射率一様性	< 1.5 % rms
― 副鏡支持スパイダー	最小限に抑える必要がある。(優先順位：２本＞４本＞３本)
― 観測波長	ミッション全体では最短観測波長は 5 µm となっているが、できる限り 3.5 µm までカバーし、4 µm 付近の惑星固有の分光フィーチャーを検出することが望ましい。

― 鏡面表面精度	装置内の可変鏡により高い精度が達成されるものの、望遠鏡による波面誤差が 2 μm 以内に収められる必要がある。

Coronagraphy of Exoplanets: The detection limit of the space coronagraphy is determined by the uniformity of the telescope transmission, and surface accuracy of the mirrors. Furthermore, the observations of short (~5 μm) is highly desired to observe exoplanets with orbital scales similar to Jupiter and Saturn in our solar system. These impose the most stringent requirements described below:

― Uniformity of Transmission	< 1.5 % rms
― Telescope Spider	should be minimized (the number = 2,4,3 in order of preference)
― Wavelength	while the SPICA mission is mainly designed for wavelengths longer than 5 μm, observations at > 3.5 μm is desired to observe a feature predicted for exoplanets at 4 μm.
― Wavefront peak-to-valley error	should be compensated using its own wavelength compensation, but should be no higher than 2 μm with the telescope optics.

他のプロジェクト（１）検出器読みだし速度およびデータ量： 惑星のトランジット分光は、距離 ＝3 - 5 pc 程度の晩期 M 型星（10μmで 4 - 5 等）がターゲットとなる。その場合、低分散分光でも１秒程度で光電荷が飽和するため、高速読み出しが必要となる。サイエンスの面から必要な時間分解能は１０分のオーダーのため、データ転送量軽減のためデータをまずオンボードで足し合わせ、地上転送する必要がある。

Other Project (1) detector reading and transfer rate: Spectroscopy of transiting planets will target late M stars at 3-5 pc (4-5 mag.@10μm). Since the targets are very bright, this project requires fast reading (<1 sec). The data corresponding to ~10 min. (i.e., integration acceptable for the science goal) should thus be stuck at the telescope before transferring to the ground in order to achieve a feasible data transfer rate.

他のプロジェクト（２）コンフュージョン： 3.2.1 節に記述されたコンフュージョンの問題は、遠赤外域でのデブリ円盤の探査に影響する(#3)。口径に対する検出限界の依存性は中間赤外ほどではないものの、より大口径での観測が望ましい。

なお、太陽系内小天体についても遠赤外域での撮像を行うが、他の多くの観測と異なり天体自身が運動するため、複数回の観測によりコンフュージョンノイズを軽減ことができる。

Other Project (2): Source Confusion: The source confusion described in 3.2.1 affects the detection limit to search for debris disks in the far infrared (#3). The dependence of the detection limit on the telescope diameter is less crucial than some extragalactic projects, due to observing wavelengths, though a larger diameter is preferred to achieve the science goal.

Note that the FIR observations of solar system small bodies is not affected by the source confusion. Since these are moving targets, we would be able to minimize the confusion noise due to different exposures at multiple epochs.

4.　トレーザビリティ、根拠資料 Traceability Documents

4.1.　SPICA ミッション要求の提示履歴 Presentation Log to Stake-holders

　ミッション要求は SPICA を取り巻くステークホルダーと共有されている事が重要である。ステークホルダーの意見・期待・ニーズが的確にミッション要求書に取り入れられていることを示すため、「何時」「誰から」「どの様に」提示されたかの履歴を表 4-1 に記録として記す。

表 4-1 SPICA ミッション要求の提示履歴

提示時期	説明者	対象	提示資料
MDR	次期赤外線天文衛星ワーキンググループ	宇宙理学委員会	SPICA ミッション提案書(第 2 版)
プロジェクト準備審査	宇宙科学研究本部	JAXA 経営者	プロジェクト準備審査説明資料 (ミッション提案書からの抜粋)
概念設計キックオフ	SPICA プリプロジェクトチーム	JAXA DE 組織 JAXA SE 部門	ミッション要求書 NC 版
概念設計フェーズ	光赤天連 SPICA タスクフォース＆SPICA プリプロジェクトチーム	光学赤外線天文連絡会・日本天文学会	ミッション要求書A版ドラフト

4.2.　SPICA 関連の政策文書（抜粋）Related Political Documents

●我が国における宇宙開発利用の基本戦略
　（平成１６年９月９日　総合科学技術会議）

２．宇宙開発利用の意義、目標及び方針

（１）意義

③地球・人類の持続的発展と国の矜持への貢献

　宇宙開発利用は、長期的視点から地球システムの持続的発展を目指すため、地球環境の現状と人類活動の及ぼす影響を全地球的規模で把握するために、もっとも有効な手段である。また、フロンティアとしての宇宙への挑戦を続けることは、国民に夢と希望を与えるとともに、国際社会における我が国の品格と地位を高めることにも大きく貢献する。

（２）目標

③知の創造と人類の持続的発展

　多くの人々に夢や希望を与えるべく、未知のフロンティアとしての宇宙に挑む。宇宙空間を探査し、利用することにより、宇宙の起源、地球の諸現象などに関する根源的な知識・知見を獲得する。さら

に、地球の有限性が語られるようになった今日、宇宙からの視点を活用して、人類の活動と地球環境との共生を目ざすとともに、更なる飛躍を求めて、宇宙における人類活動の場を拡大する。

（３）方針

我が国の国際的地位、存立基盤を確保するため、諸外国における宇宙開発利用の状況を踏まえつつ、我が国は人工衛星と宇宙輸送システムを必要な時に、独自に宇宙空間に打ち上げる能力を将来にわたって維持することを、我が国の宇宙開発利用の基本方針とする。

そのため、技術の維持・開発においては、信頼性の確保を最重視する。また、重要技術の自律性を高めるため、適切な選択と重点化を行った上で、ソフト面も含めた基盤的技術を強化するとともに、技術開発能力を維持する。

なお、研究開発目標の設定や研究開発計画の策定に関しては、利用者の要求を十分に反映することが可能となる仕組みを構築する。

４．分野別推進戦略

（３）宇宙科学研究

宇宙科学研究は、真理の追究、知の創造に寄与し、多くの人に夢、誇り及び活力を与えるものであり、宇宙開発利用の柱の一つである。

我が国の独自性を重視した研究開発を推進し、国際的水準の活動を持続する。我が国として独自性を発揮できる、太陽系探査や天文観測などの分野を中心に、資源を集中する。また、国際協力の重要性に配慮した上で、我が国の独自性を発揮できる戦略をとる。欧米などの当該分野の取組みに対しては、その状況を十分踏まえた上で、競争、連携あるいは補完の形をとる。対象分野の選択に当たっては、関連コミュニティの合意と適切な外部評価（他分野の関係者も含める）の下に、透明性を持って実施する。

（６）長期的視野に立つ研究開発の方向性

③宇宙科学研究の目指すべき方向

我が国の独自性を打ち出せる、特色ある太陽系探査や天文観測などを推進する。その際には、宇宙物理学や惑星物理学などの基礎科学研究の目指すべき長期的方向性を十分に勘案しつつ、我が国における宇宙科学研究として、知の創造に貢献できる分野に焦点を合わせる必要がある。

●宇宙開発に関する長期的な計画

（平成２０年２月２２日　総務大臣、文部科学大臣）

１．我が国の宇宙開発に関する基本的な考え方

（１）我が国の宇宙開発の目的

宇宙開発利用を取り巻く国内外の情勢を踏まえ、中長期的な展望に基づく我が国の宇宙政策を策定するに当たり、これまでの我が国の宇宙政策との整合にも配慮しつつ、我が国が宇宙開発を進める目的と意義を以下のとおり位置付け、我が国の宇宙開発のよって立つべき柱とする。

○　我が国は以下の目的の下に宇宙開発を行うものとする。
①　国及び国民の安全と安心の確保
②　宇宙空間を活用した社会基盤の整備・拡充
③　未知のフロンティアたる宇宙への挑戦

（中略）

「未知のフロンティアたる宇宙への挑戦」の下では、先進的な宇宙科学ミッションや魅力的かつ先駆的な宇宙探査等のミッションに挑戦し、人類全体の知的欲求に応えるとともに、我が国の宇宙開発活動を支える技術へ成長する可能性を秘めた革新的・萌芽的な技術の創出を目指す。

また、これらの目的に応じた便益や成果を目指すことは、以下のような国として希求する意義に大きく寄与する。

ア）人類の知的資産の拡大・深化

宇宙科学は、人類の知的資産形成に極めて重要な分野である。このため、宇宙科学への積極的な取組は、我が国が人類の知的資産の蓄積に積極的に寄与するという意志を国民と国際社会に明示することとなる。また、宇宙科学研究の推進や宇宙開発の成果に端を発する技術革新の促進は、我が国における知的活動を活性化することにつながるものである。

２．宇宙開発利用の戦略的推進

（２）宇宙科学研究の推進

宇宙科学研究は、「宇宙がどのように成立し、どのような法則によって支配されているのか」を知るための高度な知的活動であるとともに、宇宙開発に新しい芽をもたらす可能性を秘めた革新的・萌芽的な技術の源泉であり、宇宙開発利用の基盤を支えるものとして、我が国の宇宙開発利用の持続的発展のために不可欠なものである。また、我が国は、これまでにＸ線天文学や太陽・地球磁気圏観測などにおいて、高い創造性・先導性を有する世界第一線級の成果を上げてきている。

このため、以下の方針により、宇宙科学研究を推進することとする。

○　長期的な展望に基づき、我が国の特長を活かした独創的かつ先端的な宇宙科学研究を推進する。

国内外の関係する研究者グループとの密接な連携の下、研究者の自由な発想に基づく研究計画からピア・レビューを通じて精選し、我が国の特長を活かして、科学衛星の打上げ・運用や理学的・工学的研究など独創的かつ先端的な宇宙科学研究を継続的に実施し、世界最高水準の成果の創出を目指す。

今後重点を置く研究分野は、世界において広く認められる重要な科学目標を有していること、目標及び実現手段における高い独創性と技術及び予算の観点から高い実現可能性を有していること、我が国の独自性と特徴が明確であること、並びに我が国が既に世界第一級にある分野をのばすとともに、これからを担う新しい学問分野を開拓することにも留意することの観点から、以下のとおりとし、ミ

ッションに即した多様な規模の計画を展開する。

ア）宇宙空間からの宇宙物理学及び天文学

地上で実施できない観測を宇宙から行うことにより、宇宙の大規模構造から惑星系に至る宇宙の構造と成り立ちを解明するとともに、暗黒物質・暗黒エネルギーを探求し、宇宙の極限状態と非熱的エネルギー宇宙を探る。

イ）太陽系探査による科学研究

太陽、地球、惑星、始原天体及び太陽系空間環境を多様な手段で調査し、太陽系諸天体の構造、起源と進化、惑星環境の変遷、これらを通じた宇宙に共通な物理プロセスを探るとともに、太陽系惑星における生命発生、存続の可能性及びその条件を解明する。

●宇宙科学研究の推進について（報告）
（平成１８年１２月２１日　宇宙開発委員会計画部会
宇宙科学ワーキンググループ）

第２章　宇宙科学研究における長期的な展望

３．今後のプロジェクト研究の重点分野について

（２）各重点分野のプロジェクト研究の目標

①宇宙空間からの宇宙物理学及び天文学

1)宇宙の大規模構造とその成り立ちを解明し、暗黒物質・暗黒エネルギーを探る。

ア．長期的な目標

我が国が優位性を持つ赤外線、Ｘ線、ガンマ線及び電波を用いた宇宙観測により、宇宙の大規模構造の姿を捉え、基本的物質であるバリオンや様々なエネルギーの宇宙における存在形態を探ることにより、宇宙の基本構造を解明する。宇宙の初期揺らぎから現在の宇宙の大規模構造に至るまでの過程を解明し、暗黒物質の果たす役割、暗黒エネルギーと宇宙の状態及び進化との関係を探る。

イ．今後５年程度の目標

赤外線天文衛星「あかり」による全天サーベイにより宇宙地図を作成し、銀河進化の解明に資する。Ｘ線天文衛星「すざく」による銀河団等の観測研究を発展させるとともに、大気球や小型衛星等による萌芽的なミッションの開拓を行う。

ウ．２０年先を視野に入れた今後１０年程度の目標

軟Ｘ線精密撮像分光観測による熱的な宇宙の詳細観測を実現する。銀河の誕生過程及び銀河団の進化を解明するために、高解像度赤外線観測衛星及び大型Ｘ線望遠鏡衛星等の大型国際ミッションを推進する。銀河構造を解明することを目的とした高精度位置天文観測衛星の実現に必要な技術開発を行う。

2)太陽系外惑星の直接観測により惑星の形成過程を探る。

ア．長期的な目標

太陽系外惑星の直接観測により、惑星の形成過程を解明するとともに、生命が存続する可能性のある惑星を探る。

イ．今後５年程度の目標

赤外線天文衛星「あかり」により、惑星誕生環境を探る。太陽系外惑星の直接観測を目的とした次世代高解像度赤外観測衛星の実現に必要な技術開発を行う。

ウ．２０年先を視野に入れた今後１０年程度の目標

次世代高解像度赤外線観測衛星により木星型系外惑星の直接観測を実現する。地球型系外惑星の観測に必要な研究開発を行う。

●衛星の信頼性を向上するための今後の対策について

（平成１７年３月１８日　宇宙開発委員会　推進部会）

３．調査審議の結果　（１）ＪＡＸＡの衛星開発に関する基本的な考え方

ｉ）目的を明確に区別した衛星開発の徹底

・今後の衛星開発においては、実利用の技術実証を主目的とするものと、技術開発自体や科学を目的とするものを峻別して、その衛星の開発計画を企画立案する。

ⅱ）目的に応じた衛星の開発

②技術開発や科学を目的とした衛星の開発

・科学衛星については、世界初を目指す挑戦的な取組みに合った、衛星の開発を行う。

・技術開発や科学を目的とした衛星の開発においても、信頼性の確保に十分配慮する必要があり、これらの衛星のバスの開発についても、その目的を達成するために必要な技術開発を行う部分以外は、既存技術をできる限り活用するとともに、新規技術を採用する際には、地上試験や解析等によって信頼性を確保する。

ⅲ）開発期間の短縮

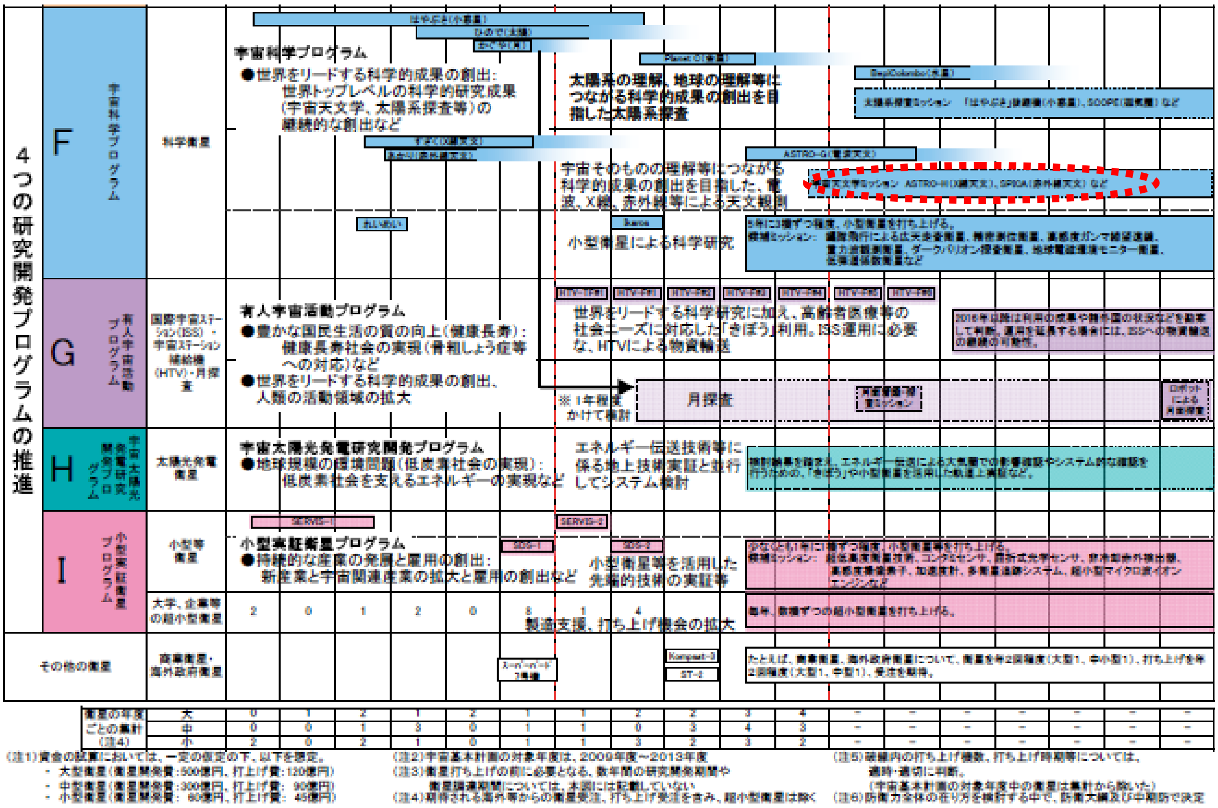
・先ず、予備設計の前（研究の段階）に十分な資源を投入するとともに、計画の企画立案時には、プロジェクトの目標を明確にした適切な開発計画を立て、プロジェクト全体の技術的な実現可能性についての検討及び審査を徹底的に行うことが必要である。予備設計を開始する時点では、既に重要な開発要素は概ね完了し、その他の要素についてもその後の開発研究及び開発の段階で解決すべき課題とその解決方法が見通せていることが必要である。

・今後の衛星の開発期間（予備設計が開始され、開発が終了するまでの期間）を、計画段階において５年程度以内を目途とし、その実現を図っていく。ただし、信頼性を一層向上する等の観点から、真に止むを得ない場合にあっては、宇宙開発委員会における計画の事前評価の段階でその必要性を十分に吟味の上、この期間を超えることもあり得る。

●宇宙基本計画　～日本の英知が宇宙を動かす～

（平成２１年６月２日　宇宙開発戦略本部決定）

別紙２「９つの主なニーズに対応した５年間の人工衛星等の開発計画（10 年程度を視野）」



●2010 年　日本学術会議記録　「天文学・宇宙物理学の展望と長期計画」

日本学術会議物理学委員会　天文学・宇宙物理学分科会

天文学・宇宙物理学長期計画小委員会（委員長　佐藤勝彦）要旨

本小委員会は 天文学・宇宙物理学分野コミュニティーを代表して我が国の天文学・宇宙物理学分野の 10～20 年を見通す展望と長期計画のとりまとめを進め、その中でも次の三つの大型計画は特に日本のコミュニティー全体が一丸となって早急に実現すべき計画である。

・重力波観測計画 LCGT

・次期大型光学赤外線望遠鏡計画 TMT

・衛星搭載次世代赤外線望遠鏡計画 SPICA

●独立行政法人宇宙航空研究開発機構が達成すべき業務運営に関する目標（中期目標）

（平成２０年４月１日　総務大臣、文部科学大臣）

Ⅱ．国民に対して提供するサービスその他の業務の質の向上に関する事項

2．宇宙科学研究

人類の知的資産及び我が国の宇宙開発利用に新しい芽をもたらす可能性を秘めた革新的・萌芽的な技術の形成を目的とし、宇宙空間からの宇宙物理学及び天文学、太陽系探査、宇宙環境利用並びに工学の分野において、長期的な展望に基づき、我が国の特長を活かした独創的かつ先端的な宇宙科学研究を推進し、世界的な研究成果をあげる。

（１）大学共同利用システムを基本とした学術研究

宇宙科学研究における世界的な拠点として、研究者の自主性の尊重、新たな重要学問分野の開拓等の学術研究の特性にかんがみつつ、大学共同利用システム※を基本として、

宇宙の大規模構造から惑星系に至る宇宙の構造と成り立ちを解明するとともに、暗黒物質・暗黒エネルギーを探求し、宇宙の極限状態と非熱的エネルギー宇宙を探る宇宙空間からの宇宙物理学及び天文学、

太陽系諸天体の構造、起源と進化、惑星環境の変遷、これらを通じた宇宙の共通な物理プロセス等を探るとともに、太陽系惑星における生命発生、存続の可能性及びその条件を解明する太陽系探査、

生命科学分野における生命現象の普遍的な原理の解明、物質科学及び凝縮系科学分野における重力に起因する現象の解明等を目指す宇宙環境利用、

宇宙開発利用に新しい芽をもたらし、自在な科学観測・探査活動を可能とするための工学

の各分野に重点を置いて研究を実施し、人類の英知を深めるに資する世界的な研究成果を学術論文や学会発表等の場を通じて提供する。

※　大学共同利用機関法人における運営の在り方を参考にし、大学・研究所等の研究者の参画を広く求め、関係研究者の総意の下にプロジェクト等を進めるシステム

（２）宇宙科学研究プロジェクト

大学共同利用システム等を通じて国内外の研究者と連携し、学問的な展望に基づいて科学衛星、国際宇宙ステーション（ISS）搭載装置及び小型飛翔体等を研究開発・運用することにより、（１）に掲げた宇宙空間からの宇宙物理学及び天文学、太陽系探査、宇宙環境利用並びに工学の各分野に重点を置きつつ、大学共同利用システムによって選定されたプロジェクトを通じて、我が国の独自性と特徴を活かした世界一級の研究成果の創出及びこれからを担う新しい学問分野の開拓に貢献するデータを創出・提供する。その際、宇宙探査プロジェクトの機会も有効に活用する。

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SPICA プリプロジェクト

SPICA pre-project

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2.2 Birth and Evolution of Galaxies:

#1: Egami, Eiichi #2: Shirahata, Mai #3: Nagao, Tohru
#4: Imanishi, Masatoshi #5: Koyama, Yusei

2.3 Life Cycle of Interstellar Dust

#1, #2, #3: Sakon, Itsuki #4: Onaka, Takashi
#5: Kaneda, Hidehiro #6: Izumiura, Hideyuki

2.4 Studies of Exoplanets and Solar Systems

#1: Enya, Keigo #2: Takami, Michihiro #3: Yamashita, Takuya
#4: Honda, Mitsuhiko #5: Ootsubo, Takafumi

科学的目的		科学的目標	フルサクセス	エクストラサクセス
銀河の誕生と進化過程の解明	SPICAでしかできない方法で、宇宙再電離期の活発な星形成銀河の検出とその正体の解明に挑み、ダスト放射をプローブとして宇宙最初の本格的な重元素合成の時期を特定する。	宇宙初期（赤方偏移4以上、宇宙再電離時代）の活発な星形成銀河からの電離水素・水素分子・ダストバンド輝線を、それらが赤方偏移した中間・遠赤外線領域の分光観測で検出する。また銀河団重力レンズで強められた塵からの放射を検出し、赤方偏移4以上での星形成史を探る。	宇宙初期（赤方偏移4～7）の活発な星形成銀河からの電離水素・水素分子輝線、また赤方偏移10までのダストバンド輝線を、それらが赤方偏移した中間・遠赤外線領域の分光観測で検出する。また銀河団重力レンズを利用し赤方偏移4以上での星形成史を探る。 【中】	赤方偏移7以上の「種族III天体」の候補からの水素分子輝線を検出する。赤方偏移7以上のＨα輝線銀河の新たな種族を発見する。 宇宙再電離期の超巨大ブラックホール・ガンマ線バースト残光の分光スペクトルにより、その正体を解明する。 【大】
	宇宙遠赤外線背景放射の大部分を個別天体に分解するし、それでも残存する背景放射の絶対強度と空間揺らぎの起源を明らかにする。	宇宙遠赤外線背景放射を、「あかり」の3倍以上の空間分解能により個別の遠赤外線天体に分解する。さらに個別天体を取り除いた遠赤外線背景放射の絶対値とゆらぎを評価し、多波長相関解析等からその起源を解明する。	宇宙遠赤外線背景放射の大部分（80%以上）を遠赤外線天体に分解するとともに、その空間的揺らぎを担う天体の正体についての情報を、多波長空間相関解析等により入手する。 【中】	宇宙再電離期の第一世代星起源と解釈できる赤外線背景放射の空間揺らぎの検出に成功する。 再電離期の第一世代星の積分光のスペクトルの取得に成功する。 【大】
	星間塵の影響を正しく評価し補正したうえで、星間環境の診断とダスト放射の理解を基に、塵に覆われた遠方銀河の物理化学を解明する。	赤方偏移3までの銀河について、中間・遠赤外線中分散広帯域分光観測を行ない、PAH放射や原子の電離輝線・分子輝線を効率的に捕らえ、その銀河の星間環境と星間ダストの性質を明らかにする。これにより、他波長のように星間塵の吸収補正の不定性なく、初期の宇宙（90億年前まで)の銀河の物理化学状態を明らかにする。	赤方偏移2～3までの様々な銀河について、広帯域中分散分光観測の統計的研究を行うことにより、初期の宇宙（90億年前まで)の銀河の物理化学状態を明らかにする。 【中】	初期の宇宙（120億年前まで)の銀河の物理化学状態を明らかにする。（観測装置感度の達成度合いに依存） 【大】
	銀河の進化における超巨大ブラックホールの役割を解明するため、他の手法では観測が困難な星間塵に囲まれた形成中の超巨大ブラックホールを、初期宇宙にいたるまで探査する。	星間塵の影響を受けない赤外線撮像・分光観測により、他の手法では観測が困難な星間塵に囲まれた形成中の超巨大ブラックホールを、現在の宇宙から初期宇宙に至るまで広く探査し、統計的に十分な数のサンプルを構築する。これと、銀河形成史の観測結果とをくみあわせて、銀河の進化における超巨大ブラックホールの役割を解明する。	赤外線撮像・分光観測により、塵に囲まれた形成中の超巨大ブラックホールを、現在の宇宙から初期宇宙（120億年前まで）に至るまで探査し、統計的に十分な数のサンプル（候補含む）を構築する。 【中】	塵に囲まれた形成中の超巨大ブラックホールを、初期宇宙（120億年前）において多数発見し、銀河進化との関連を明らかにする。 【大】
	銀河の星形成史・質量集積史と、銀河団や宇宙大規模構造の形成過程・環境効果との関係を、初期宇宙に遡って明らかにする。	星形成活動のピークがあったとされる時代（赤方偏移1～2）、およびさらに過去の時代（赤方偏移～5まで）の銀河団・原始銀河団を静止系赤外線で徹底的にサーベイすることで、各時代・各環境下に存在する銀河の真の活動性を明らかにし、銀河団や大規模構造の形成が、宇宙星形成史・質量集積史および銀河進化にどのような影響を与えたのかを解明する。	星形成活動のピークがあったとされる時代（赤方偏移1～2）、およびさらに過去の時代（赤方偏移～5まで）の銀河団・原始銀河団領域を静止系赤外線で広く観測することで、銀河の真の星形成史・質量集積史を時間軸・環境軸に沿って明らかにする。 【中】	広大な赤外線域多波長サーベイ（およそ300MPC相当)を行い、地上からの可視光・近赤外線観測では発見し得ない、初期宇宙（赤方偏移～5まで）の赤外線銀河集団の同定に成功する。 【大】

表 2.　天文科学コミュニティが掲げる SPICA の科学目標・成功基準（1/3）

科学的目的		科学的目標	フルサクセス	エクストラサクセス
物質循環 ・星間塵の起源（形成過程、破壊過程） ・星周塵と星間塵 ・星間化学 ・銀河考古学	大質量星終焉のダスト形成過程を解明し、初期宇宙のダスト起源を探る	25Mpc以内の近傍銀河内で起こるダスト形成の兆候が見られる超新星(˜5個)について、爆発後から1～2年間に複数回のデータ取得を行う。これにより、超新星放出ガスからダストが新たに凝縮する過程、また、それらが既存の星周ダストの温度(数百度K)に冷える過程の中間赤外スペクトル変化を調べ、超新星ejecta中で形成されるダストの組成、サイズ分布、質量を詳細に制限する。([中間赤外撮像1H, 中間赤外分光2H]×10回×5targets)	25Mpc以近で起こった複数の超新星において爆発後数年にわたる中間赤外分光観測から、形成されるダストと既存のダストを区別し、組成と共にダストの形成量を精度良く見積もる。 【中】	25Mpc以近に起こった統計的に十分な数のさまざまなtypeの超新星について、爆発後数年にわたる中間赤外分光観測のデータから、ダスト形成に必要な条件に対する制限をもとめ、放出された原子ガス、ダストの先駆体となる分子ガス、ダスト放射の関係を明らかにし、大質量星によるダスト形成メカニズムを解明し初期宇宙のダストの起源を得る。 【大】
	−中・小質量星によるダスト形成過程を解明し、天の川銀河中のダスト、即ち現在の宇宙のダストの起源における中小質量星の役割を探る。	系内、及びマゼラン雲中のAGB星、惑星状星雲、新星など進化した中小質量星約30個の星周の希薄なダストシェルを空間分解し、撮像情報から過去の質量放出とダスト形成の歴史を調べる。また星周の分子・ダストシェルの中間赤外˜遠赤外分光データから、分子・ダストシェルの組成を調べ、放出ガスから形成されたダストの性質を制限する。([中間赤外撮像1H, 中間赤外分光2H, 遠赤外撮像分光2H]×30targets)	系内およびマゼラン雲内の数10個の中・小質量星の終焉において形成される分子・ダストシェルの空間構造を詳細に捉え、分子・ダスト形成メカニズムを探る。また、C-rich AGB星周囲で、可視光を熱源とする低輝度なPAH放射の有無を調べ、PAHの形成場所と形成過程に制限を与える。 【中】	晩期型星から放出された原子ガスと、ダストC-richな星の場合、(特にPAH)の先駆体となる分子ガス(acetyleneなど)、及びダスト放射の関係を、統計的に十分な数のサンプルに対して明らかにし、中・小質量星によるダスト形成メカニズムを解明し、現在の宇宙のダストの由来を理解する。また分子シェルの組成を調べMOLsphereの成因を解明する。 【大】
	−低温高密度分子雲中におけるダスト形成・成長の過程を探る。	系内の若い星を内包する系内の数10個の低温高密度分子雲の中間～遠赤外分光観測によってiron sulphideの赤外バンドを検出し、Inter planetary Dust Particles (IDPs)中に見られるGlass with Embedded Metals and Sulfides (GEMS)とInterstellar dustの関連を解明する。これによって低温高密度分子雲中におけるダスト粒子の成長のシナリオを探る。([中間赤外分光2H, 遠赤外撮像分光2H]×20targets)	sulpherのダスト層への効率的なdepletionが示唆される系内の低温高密度分子雲数10個について、JWSTではカバーされない/SPICAが感度で勝る20−45μmの分光観測からiorn suldiedの23.5, 34, 38, 44μm featuresを検出し、IDP中のGEMSの分光測定データとの類似性を結論し、分子雲中でのinterstellar dust形成と成長の可能性を探る。 【中】	低温分子雲中でのダストの粒子成長とともに、ALMAプロジェクトとの協調のもとでダスト表面における有機物分子の合成を探り、星間ダストの合成場所として分子雲の役割を理解する。 【大】
	−銀河物質進化への超新星の影響、特にダスト生成・破壊及び周囲の星間物質へのエネルギー供給過程を明らかにする。	これまで赤外線で検出されている超新星残骸（系内外あわせて約30個）について、計300　時間(TBD)の中間赤外線・遠赤外線イメージ分光を行い、生成ダスト・組成・量、衝撃派の影響・ISMへの影響を調べる。Objective#5で検出されたSNRについても同様の詳細観測も行う（約100−200 時間）	系内及びマゼラン雲において既知の超新星残骸約30個について、高感度・高空間分解中間赤外線・遠赤外線イメージ分光の情報から、ジオメトリを考慮して既存のダストと超新星放出物質起源のダストを区別した上で、生成ダストの組成・量を同定し、星間ダストへの還元のプロセスを、形成量と破壊量の収支と踏まえて理解する。【中】	空間分解されたSNRの近赤外・中間赤外及び遠赤外線イメージ分光の情報から、SNRに付随する生成ダストの組成・量を同定し、より多様な銀河環境の下で、より多くのサンプル数を得ることによって、SN放出物質の星間ダストへの還元プロセスをより普遍的な視点で理解する。銀河系内の若い中心核崩壊型SNRを近赤外分光撮像し、超新星爆発過程及びそれに伴う元素合成を理解する。 【大】
	−系外銀河内外の物質の流れを捉え、銀河スケールで物質の進化を理解する。	「あかり」サンプル近傍銀河50個に対し、計600時間の中間・遠赤外線イメージ分光により、ガス診断とダスト(バンド)観測を行う。SNR、HII領域、巨大分子雲、銀河中心、ハローなど、物質の生成・破壊場所を空間分解し、大きな循環と銀河内gradientを捉える。系内物質循環の詳細研究(#1～#4)と相補的。	大きさ5−10分角の異なるハッブル型をもつ近傍銀河50個に対し、銀河全面をカバーする、波長5−210umの低分散スペクトルマッピングデータを取得する。また、銀河中心領域に対して、波長　10−210umの中分散スペクトルマッピングデータを取得する。これらの銀河共通データセットを用いて、様々な物理環境におけるISM放射を系統的に理解する。また、遠方銀河の物理環境を診断するための道具を構築する。 【中】	未開の波長粋35−60um帯の高感度スペクトルから、新しいダストバンドやVSGs放射の空間変化に対する詳細情報を得て、銀河ハロー・銀河間空間へ流れ出る、あるいは楕円銀河やSNRの高温プラズマ中で壊されていくダストの特性変化を捉える。物質のlife cycleの終焉を正確に理解することで、将来の銀河・宇宙の運命・宿命を予知する。 【大】
	大中小質量星の織り成す物質循環の場である銀河系の構造と構成員を解明し、銀河スケールの大局的な物質循環を探る。	銀河系、特に銀河面における、繰り返し撮像サーベイと分光サーベイを計38日で実施し、10億個の天源ソースカタログと、1000万個の低分散分光カタログと、拡散光輝線スペクトルマップを得る。長周期変光星の完全探索、レッドクランプ星の完全探索、それらによる銀河系構造の探求、物質循環率の解明を進める。	恒星分布に基づく銀河系構造を明らかにし、物質循環の場そのものを理解する。特に長周期変光星の完全探索によって、新たな銀河系構造研究の手段をもたらす。【中】	未知の銀河系構造、未知の拡散光輝線成分の発見、未知のSEDを持つ天体の発見をめざす。 【大】

表2　天文科学コミュニティが掲げるSPICAの科学目標・成功基準（2/3）

科学的目的		科学的目標	フルサクセス	エクストラサクセス
惑星系形成過程の総合理解 ・形成中の円盤 （ガス、塵、構造） ・出来上がった惑星系 （残骸円盤の塵の量、 ガス惑星、氷天体）	惑星系多様性解明のため、これまで 誰も実現できていない太陽系外惑星の直接撮像による惑星大気組成の観測を、最も観測的有利な波長である赤外線領域において挑戦する。	主星：惑星のコントラスト比10＾($^{-6}$)以上の観測を実現することにより、系外ガス惑星を直接に検出すると同時に、分光観測によりその大気の組成を明らかにする。これを我々の太陽系の惑星系と比較することにより、惑星系の多様性を解明する。 トランジット法を利用した分光観測により、巨大地球型惑星の大気検出を試みる。木星型惑星については、多数の赤外分子バンドの観測により大気組成を詳細に調べる。	トランジット法を用いた分光観測により、巨大地球型惑星の大気を検出する。同様の観測を木星型惑星に行い、その大気組成を詳細に調べる。 【中】	主星：惑星のコントラスト比10^{-5}以上で近傍の100個の天体に対する系外ガス惑星の直接観測を行い、系外ガス惑星を直接検出し、その大気組成を明らかにする。 【大】
	惑星系形成領域のガスの散逸過程および構造の進化を観測し、木星型惑星の形成メカニズムや地球型惑星の生成条件を明らかにする。	若い星の周りの暖かいガス（100−1000 K）に伴う輝線を観測し、起源を確定する。原始惑星系円盤に付随する輝線を用いて残存ガスの量を求め、主星の質量や年齢との相関を解明する。 高分散赤外線分光観測によりガスのさまざまな速度成分の輝線強度比を求め、円盤の空間構造、物理状態、化学組成の分布を明らかにする。	惑星系形成領域から放射されると理論的に予測される、多数の輝線（分子、原子・イオン輝線）を多数の前主系列星について探査し、その起源を明らかにする。 スピッツァー望遠鏡による観測などで、明るい輝線の存在が既に知られる原始惑星系円盤の高分散分光を行い、惑星系形成領域の構造や物理・化学状態の分布を明らかにする。 【中】	原始惑星系円盤中の分子ガスが惑星形成とともに減少していく様子を調べ、木星型惑星生成の状況や地球型惑星生成の初期条件を明らかにする。 異なる進化段階の原始惑星系円盤を多数観測し、惑星系形成領域の構造や物理・化学状態がどのように進化していくかを明らかにする。あわせて、円盤の進化と主星の質量、連星系の有無などの関係を明らかにする。 【大】
	多数の主系列星周りの塵円盤の観測により、惑星系の普遍性および多様性を理解する。	「あかり」よりも3倍以上良い空間分解能と10倍以上すぐれた感度により、主系列星周りの塵円盤を太陽系と同程度の塵しかない円盤まで検出し、惑星系と塵円盤と相互関係を解明する。	主系列星周りの塵円盤を、近傍(<20pc)の系については太陽系の10倍程度の塵円盤まで検出し、塵の豊富な系については1kpcの距離に至るまで検出する。	主系列星周りの塵円盤を、近傍(<20pc)の系については太陽系と同程度の塵しかない円盤まで検出し、塵の豊富な系については金属量との関係を明らかにする。 【大】
	惑星系形成過程における氷の役割と、生命の起源につながる固体物質の供給過程の解明のために、原始惑星系円盤や主系列星の塵 円盤中の固体物質、特に氷の分布、物理状態を明らかにする。	コロナグラフを用いて原始惑星系円盤および主系列星の塵円盤の高感度観測を行い、その進化的関係を明らかにする。 主系列星の塵 円盤を、「あかり」よりも3倍以上良い空間分解で赤外線分光観測することにより、固体物質、特に氷および微小惑星帯の分布や物理状態を明らかにする。	100個の原始惑星系円盤や主系列星の塵 円盤を、「あかり」よりも3倍以上良い空間分解能で赤外線分光観測する。 【中】	いくつかの星生成領域を含む、150 pc以内の原始惑星系円盤や主系列星の塵円盤について、系統的な赤外線分光観測を行う。 【大】
	我々の太陽系の姿を明確にし、探査機による太陽系天体の観測結果と天文学的手法による惑星系観測結果を結ぶため、太陽系内の始原天体である氷天体を、太陽系外縁部まで調査する。	「あかり」よりも10倍以上すぐれた感度により、太陽系内の氷天体からの熱放射を、太陽系外縁部まではじめて調査し、アルベド・サイズ・熱慣性・組成などを決定する。	太陽系外縁部（30−50AU）にある直径が100km以下の氷天体からの熱放射をはじめて検出する。サイズ・アルベド・熱慣性の分布と軌道との相関を調べ、太陽系外縁部の進化の履歴を明らかにする。【中】	太陽系外縁天体について系統的な遠赤外線分光観測を初めておこない、表面の氷・鉱物の組成を明らかにする。 【大】

ミニマムサクセス
上記の基準のうち、【中】を2つ以上達成すること。

表２　天文科学コミュニティが掲げる SPICA の科学目標・成功基準（3/3）

科学的目標	ミッション要求										
	コアとなる波長領域	望遠鏡の温度	望遠鏡の口径（集光力）	望遠鏡の口径（解像度,WFEの要求あり）	感度	波長分解能（λ/⊿λ）	観測装置の視野	観測期間	運用（時期）	データ量（平均、ピーク）	観測装置
宇宙初期（赤方偏移4以上、宇宙再電離時代）の活発な星形成銀河からの電離水素・水素分子・ダストバンド輝線を、それらが赤方偏移した中間・遠赤外線領域の分光観測で検出する。また銀河団重力レンズで強められた塵からの放射を検出し、赤方偏移4以上での星形成史を探る。	[full success] 中間赤外、遠赤外線 [extra success] 近赤外	[Full Success] 6.0K以下 [Extra Success] 5.5K以下	3m級以上	3m級以上	1E−20 W/m2 以上	[full success] SAFARI > 700 [extra success] BLISS > 700	SAFARI: >2arcmin MIRACLE: >6 arcmin	2年以上	JWST, TMT	平均＜1Mbps ピーク2Mbps	[full success] MIRACLE SAFARI [extra success] BLISS FPC-S
宇宙遠赤外線背景放射を、「あかり」の3倍以上の空間分解能により個別の遠赤外線天体に分解する。さらに個別天体を取り除いた遠赤外線背景放射の絶対値とゆらぎを評価し、多波長相関解析等からその起源を解明する。	[full success] 遠赤外 [extra success] 近赤外	[Full Success] 6.0K以下 [Extra Success] 5.5K以下	2.5m以上	2.5m以上	撮像： 100uJy @ 70um(フル） 50uJy@70um（エクストラ）	several (imaging) SAFARI > 700	＞ 1 arcmin	1年以上	ALMA	平均＜4Mbps ピークTBD	[full success] MIRACLE SAFARI [extra success] BLISS FPC-S
赤方偏移3までの銀河について、中間・遠赤外線中分散広帯域分光観測を行ない、PAH放射や原子の電離輝線・分子輝線を効率的に捕らえ、その銀河の星間環境と星間ダストの性質を明らかにする。これにより、他波長のように星間塵の吸収補正の不定性なく、初期の宇宙（90億年前まで）の銀河の物理化学状態を明らかにする。	中間赤外、遠赤外線	6.0K以下（フルサクセス） 5.5K以下（エクストラサクセス）	3m級以上	2.5m以上	分光（遠赤外）： 1E−19 W/m2 （フル） 1E−20 W/m2 （エクストラ）	Spectr.: 100 & >700	＞ 1 arcmin	1年以上	JWST, TMT. ALMA	平均＜4Mbps ピークTBD	MIRACLE MIRMES SAFARI BLISS
星間塵の影響を受けない赤外線撮像・分光観測により、他の手法では観測が困難な星間塵に囲まれた形成中の超巨大ブラックホールを、現在の宇宙から初期宇宙に至るまで広く探査し、統計的に十分な数のサンプルを構築する。これと、銀河形成史の観測結果とをくみあわせて、銀河の進化における超巨大ブラックホールの役割を解明する。	中間赤外、遠赤外線	6.0K以下（フルサクセス）	2.5m以上（full success） 3m級以上（extra）	3m級以上	20uJy @20um（フル）	imaging : several Spectr. >100	＞ 1 arcmin	1年以上	JWST, TMT, IXO	平均 0.33 − 1.6Mbps ピーク 3.94Mbps	MIRACLE MIRMES SAFARI
星形成活動のピークがあったとされる時代（赤方偏移１～２）、およびさらに過去の時代（赤方偏移～５まで）の銀河団・原始銀河団を静止系赤外線で徹底的にサーベイすることで、各時代・各環境下に存在する銀河の真の活動性を明らかにし、銀河団や大規模構造の形成が、宇宙星形成史・質量集積史および銀河進化にどのような影響を与えたのかを解明する。	中間赤外、遠赤外線	6.0K以下（フルサクセス） 5.5K以下（エクストラサクセス）	3m級以上	3m級以上	中間赤外： 5uJy（フル） 1uJy（エクストラ） 遠赤外： 100uJy（フル） 50uJy（エクストラ）	several (imaging)	＞ 4 arcmin （フルサクセス） ＞ 6 arcmin （エクストラサクセス）	1年以上	JWST, TMT	平均＜4Mbps ピークTBD	MIRACLE SAFARI

表 3. 天文科学コミュニティが掲げる SPICA のミッション要求（1/3）

科学的目標	コアとなる波長領域	望遠鏡の温度	望遠鏡の口径（集光力）	望遠鏡の口径（解像度,WFEの要求あり）	感度	波長分解能（λ/⊿λ）	観測装置の視野	観測期間	運用（時期）	データ量（平均、ピーク）	観測装置
~25Mpc以内の近傍銀河内で起こるダスト形成の兆候が見られる超新星(~5個以上)について、爆発後から1～2年間に複数回のデータ取得を行う。これにより、超新星放出ガスからダストが新たに凝縮する過程、また、それらが既存の星周ダストの温度(数百度K)に冷える過程の中間赤外スペクトル変化を調べ、超新星ejecta中で形成されるダストの組成、サイズ分布、質量を詳細に制限する。	中間赤外線、遠赤外線 (4-200μm)	6K以下	3m級以上	3m級以上	MIRACLE: IRS SL&LLの1桁高 MIRMES: IRS SH&LHの1桁高 SAFARI: PACSの2桁高	MIRACLE:＞100 MIRMES:＞1000 SAFARI:＞1000	中間赤外線低分散:>1 arcmin 中間赤外線中分散:～10 arcsec 遠赤外線:>1 arcmin	2年以上（Herschel相当かそれ以上。近傍超新星爆発の頻度を考慮）	JWSTとは独立。Mission中に適した超新星がでれば十分に意味がありユニークである。	(平均) <500Kbps (ピーク) 2Mbps	MIRACLE、MIRMES、SAFARI
系内、及びマゼラン雲中のAGB星、惑星状星雲、新星など進化した中小質量星約30個の星周の希薄なダストシェルを空間分解し、撮像情報から過去の質量放出とダスト形成の歴史を調べる。また星周の分子・ダストシェルの中間赤外~遠赤外分光データから、分子・ダストシェルの組成を調べ、放出ガスから形成されたダストの性質を制限する。	中間赤外線、遠赤外線 (4-200μm)	6K以下	2m級以上	波長10um回折限界（MIRMESの波長カバレッジの短波長端）	MIRACLE: IRS SL&LLの1桁高 MIRMES: IRS SH&LHの1桁高 SAFARI: PACSの2桁高	MIRACLE:＞100 MIRMES:＞600 MIRHES:＞10000 SAFARI:＞1000	中間赤外線低分散:>1 arcmin 中間赤外線中分散:～10 arcsec, 高分散:～a few arcsec, 遠赤外線: >1 arcmin	2年以上（Herschel相当かそれ以上。）	JWSTの成果が出た後。ターゲットの最終絞込みで考慮。我々のデータの波長範囲はユニークであり、急ぐ必要なし。	(平均) <2Mbps (ピーク) ~4Mbps	MIRACLE、MIRMES、SAFARI
系内の若い星を内包するcold dense molecular cloudsの中間~遠赤外分光観測によってiron sulphideの赤外バンドを検出し、Inter planetary Dust Particles (IDPs)中に見られるGlass with Embedded Metals and Sulfides (GEMS)とInterstellar dustの関連を解明する。これによってsuperparamagnetic (SPM) hypothesis の検証を行い、低温高密度分子雲中におけるダスト粒子の成長のシナリオを探る。	中間赤外線、遠赤外線 (4-200μm)	6K以下	3m級以上	3m級以上	MIRACLE: IRS SL&LLの1桁高 MIRMES: IRS SH&LHの1桁高 HIRES: IRS SH&LHと同程度 SAFARI: PACSの2桁高	MIRMES:＞600 MIRHES＞10000 SAFARI:＞1000	中間赤外線中分散:～10 arcsec 中間赤外線高分散:～a few arcsec 遠赤外線:～5 arcmin	2年以上（Herschel相当かそれ以上。Object #1-2の結果をfeadbackすることを計画）	JWSTの成果が出た後。ターゲットの最終絞込みに必要。中間赤外高分散機能、中分散中間赤外～遠赤外の波長範囲はユニーク。	(平均) <500Kbps (ピーク) 2Mbps	MIRACLE、MIRMES、MIRHES, SAFARI
現在までに赤外線で検出されている系内・系外超新星残骸約30個に対して、中間赤外から遠赤外線までの空間分解した中分散撮像を行う。またobject#3の観測結果をfeedbackし、系外銀河に新たに検出される超新星残骸についても同様の観測を行い、超新星のejectaに伴うダスト量・組成及び周囲の星間物質との相互作用から星間物質の進化への超新星の寄与を解明する。観測時間は300-500時間程度を予定する。	[full success] 中間赤外線、遠赤外線 [extra success] 近赤外	6K以下	3m級以上	波長10um回折限界（MIRMESの波長カバレッジの短波長端）	拡散光に対して、MIRACLE: IRS SL&LLの1桁高 MIRMES: IRS SH&LHの1桁高 SAFARI: PACSの2桁高	MIRACLE:＞100 MIRMES:＞1000 SAFARI:2つのモードが必要、100/2000	中間赤外線低分散:～5 arcmin 中間赤外線中分散:～10 arcsec 遠赤外線:～5 arcmin	2年以上（Herschel相当かそれ以上。Ojbect#3の結果をfeedbackすることを計画）	JWSTとは独立。JWSTではガスとの相互作用は研究できるが、ダストについてはSPICAの機能が必須。	(平均) <500Kbps (ピーク) 2Mbps	[full success] MIRACLE MIRMES SAFARI [extra success] FPC-S
「あかり」サンプル近傍銀河50個に対し、計600時間の中間・遠赤外線イメージ分光により、ガス診断とダスト(バンド)観測を行う。SNR、HII領域、巨大分子雲、銀河中心、ハローなど、物質の生成・破壊場所を空間分解し、大きな循環と銀河内gradientを捉える。系内物質循環の詳細研究(#1&#2)と相補的。	中間赤外線、遠赤外線	6K以下	3m級以上	波長10um回折限界（MIRMESの波長カバレッジの短波長端）	MIRACLE: IRS SL&LLの1桁高 MIRMES: IRS SH&LHの1桁高 SAFARI: PACSの2桁高	MIRACLE:＞100 MIRMES:＞1000 SAFARI:2つのモードが必要、100/2000	中間赤外線低分散:～5 arcmin 中間赤外線中分散:～10 arcsec 遠赤外線:～5 arcmin	2年以上（Herschel相当かそれ以上、我々の観測時間600hrは、Hercschel近傍銀河プログラムKingfish相当）	JWSTの成果が出た後。ターゲットの最終絞込みに必要。我々のデータの波長範囲はユニークであるため、急ぐ必要なし。	(平均) <500Kbps (ピーク) 2Mbps	MIRACLE、MIRMES、SAFARI
銀河系、特に銀河面における、繰り返し撮像サーベイと分光サーベイを計38日で実施し、10億個の天源ソースカタログと、1000万個の低分散分光カタログと、拡散光輝線スペクトルマップを得る。長周期変光星の完全探索、レッドクランプ星の完全探索、それらによる銀河系構造の探求、物質循環率の解明を進める。	[full success] 中間赤外線 [extra success] 近赤外線	6K以下	2m級以上	3m級以上	FPC-S: Spitzer/IRACの1桁高 MIRACLE: IRS SH&LHの1桁高	MIRACLE:＞100	中間赤外線低分散:～5 arcmin 近赤外撮像:～5arcmin	2年以上（Herschel相当かそれ以上）	我々のデータの波長範囲はユニークであるため、急ぐ必要なし。	(平均) 2Mbps (ピーク) ~4Mbps	[full success] MIRACLE [extra success] FPC-S

表 3. 天文科学コミュニティが掲げる SPICA のミッション要求（2/3）

科学的目標	コアとなる波長領域	望遠鏡の温度	望遠鏡の口径（集光力）	望遠鏡の口径（解像度,WFEの要求あり）	感度	波長分解能（λ/⊿λ）	観測装置の視野	観測期間	運用（時期）	データ量（平均、ピーク）	観測装置
主星：惑星のコントラスト比10^(−6)以上の観測を実現することにより、系外ガス惑星を直接に検出すると同時に、分光観測によりその大気の組成を明らかにする。これを我々の太陽系の惑星系と比較することにより、惑星系の多様性を解明する。 トランジット法を利用した分光観測により、巨大地球型惑星の大気検出を試みる。木星型惑星については、多数の赤外分子バンドの観測により大気組成を詳細に調べる。	中間赤外	10K以下	3 m級以上	3 m級以上	1μJy @λ5μm	>200	＞0.5 arcmin	1年以上	JWST, TMT, 8m−EXAO	(平均) <500Kbps (ピーク) 2Mbps	[Full success] MIRMES MIRHES [Extra success] SCI
若い星の周りの暖かいガス（100−1000 K）に伴う輝線を観測し、起源を確定する。原始惑星系円盤に付随する輝線を用いて残存ガスの量を求め、主星の質量や年齢との相関を解明する。	中間赤外、遠赤外線	6.0K以下（フルサクセス） 5.5K以下（エクストラサクセス）	2 m以上	3 m級以上 （エクストラサクセス）	10^−19 W/m^2	>600	数秒	1年以上	TMT, ALMA	(平均) <500Kbps (ピーク) 2Mbps	MIRMES MIRHES SAFARI
高分散赤外線分光観測によりガスのさまざまな速度成分の輝線強度比を求め、円盤の空間構造、物理状態、化学組成の分布を明らかにする。	中間赤外	10K以下	3 m級以上	3 m級以上 （エクストラサクセス）	10^−19 W/m^2	＞30,000	数秒	1年以上	TMT, ALMA	(平均) <500Kbps (ピーク) 2Mbps	MIRHES
「あかり」よりも3倍以上良い空間分解能と10倍以上すぐれた感度により、主系列星周りの塵円盤を太陽系と同程度の塵しかない円盤まで検出し、惑星系と塵円盤と相互関係を解明する。	中間赤外、遠赤外線	6.0K以下（フルサクセス） 5.5K以下（エクストラサクセス）	2 m以上	3 m級以上	10 μJy	5	＞1.5 arcmin	1年以上	JWST, ALMA	(平均) <500Kbps (ピーク) 2Mbps	MIRACLE SAFARI
コロナグラフを用いて主系列星の塵円盤や原始惑星系円盤の高感度観測を行い、その進化的関係を明らかにする。	中間赤外	10K以下	3 m級以上	3 m級以上	10μJy arcsec^{-2} @λ5μm	100	＞0.5 arcmin	1年以上	JWST, TMT	(平均) <500Kbps (ピーク) 2Mbps	[Extra success] SCI
主系列星の塵 円盤を、「あかり」よりも3倍以上良い空間分解で赤外線分光観測することにより、固体物質、特に氷および微小惑星帯の分布や物理状態を明らかにする。	遠赤外・中間赤外	6.0K以下（フルサクセス） 5.5K以下（エクストラサクセス）	2 m以上	3 m級以上	100μJy (<λ40μm) 1 mJy (>λ40μm)	100	＞1 arcmin	1年以上	JWST, TMT, ALMA	(平均) <500Kbps (ピーク) 2Mbps	MIRMES MIRACLE SAFARI
「あかり」よりも10倍以上すぐれた感度により、太陽系内の氷天体からの熱放射を、太陽系外縁部まではじめて調査し、アルベド・サイズ・熱慣性・組成などを決定する。	遠赤外	6.0K以下（フルサクセス） 5.5K以下（エクストラサクセス）	3 m級以上	—	50−100μJy（測光、遠赤外線） （confusion 限界をのぞく） 1mJy（分光、遠赤外線）	5−100	＞1 arcmin	1年以上	JWST, TMT	(平均) <500Kbps (ピーク) 2Mbps	SAFARI

表 3. 天文科学コミュニティが掲げる SPICA のミッション要求（3/3）

Scientific Objectives		Scienetific Targets	Full Success	Extra Success
Resolution of Birth and Evolution of Galaxies	With SPICA's unique capability we will discover active star-forming galaxies at re-ionization epoch, and reveal their nature. By using dust emission as a probe, we will identify the major epoch of heavy element production.	We will search for redshifted ionized H lines, H_2 lines and dust emission band (z>4, at re-ionization epoch) from active star-forming galaxies with mid-& far-IR spectroscopy. We also search for star-forming galaxies at z>4 by using flux magnification due to cluster gravitational lens at z>4.	We will detect H-recombinationlines, molecular hydrogen lines from active star-forming galaxies at z=4-7, and dust-band emission out to z=10. We may also utilize the cluster gravitational lens in search for the star-formation history beyond z=4. [moderate impact]	We will detect molecular hydrogen emission lines from population III objects, new H_alpha emission population beyond z=7. Spectroscopic studies of Super-massive Black-Holes and Gamma-Ray Burst after glow at reionization epoch reveals their nature. [large impact]
	We will resolve the cosmic far-infrared background light into individual objects, and reveal the origin of the cosmic far-infrared background residual brightness and fluctuations.	We will resolve the cosmic far-infrared background light into individual far-infrared objects with 3 times or more higher spatial resolution than that of AKARI. We then evaluate far-infrared background residual brightness and its fluctuations after removal of the individual objects, and reveal its origin through detailed analysis such as multi-wavelength correlation.	We can resolve more than 80% of the cosmic far-infrared background light into the individual far-infrared objects. We also obtain the information about the objects which contribute the fluctuation of the cosmic far-infrared background, through the detailed analysis such as multi-wavelength correlation. [moderate impact]	We successfully obtain the detection of the fluctuation of the cosmic near- and far-infrared background that can be interpreted as the emission originated from the 1st stars at the re-ionization epoch of the universe. We will obtain the spectrum of the integrated light of 1st stars at the re-ionization epoch. [large impact]
	We will reveal physical & chemical condition of high-z galaxies with precise correction for dust attenuation, based on understanding of interstellar environment and dust emission.	We will reveal interstellar environment and dust emission characteristics of high-redshift galaxies out to z~3 through PAH emission as well as atomic and molecular emission lines with broad-band mid- & far-IR moderate resolution spectroscopy. These observations allow us to reveal the physical & chemical conditions of dusty galaxies in the early universe (up to 9 Gyr ago) with precise correction for dust attenuation.	We will reveal the physical and chemical conditions of galaxies in the early universe (up to 9 Gyr ago) by statistically significant number of samples up to redshifts of z=2-3 with moderate resolution spectroscopy in the mid- and far-infrared wavelength. [moderate impact]	Revealing the physical and chemical conditions of galaxies in the early universe (up to 12 Gyr ago, depending on the achieved sensitivity of the instruments). [large impact]
	In order to understand the role of supper-massive black holes (SMBHs) in the galaxy evolution, we will make a survey for the forming SMBHs, that may not be observed easily in other methods due to the obscuration by dust, from the present to the early universe.	We will make infrared imaging & spectroscopic observations of statistically meaningful number of candidates in search for the forming super-massive black holes (SMBHs), that can not be observed easily in other methods due to the obscuration of dust, from the present to the early universe. Supplementing these results with the results of observations for the galaxy formation history, we will understand the role of SMBHs in the galaxy evolution.	We perform infrared photometry and spectroscopic observations of a thousand dust-obscured embryonic super massive black-holes (including candidates) in the universe, up to 12 Gyr ago. [moderate impact]	We identify dust-obscured embryonic super massive black-holes in the early universe, up to 12 Gyr ago, and reveal their role in galaxy formation and evolution. [large impact]
	We will reveal the star-formation & mass assembly history of galaxies from the early universe, in relation to the forming processes of the galaxy clusters and the large scale structures, as well as the environmental effect on the galaxy evolution.	We will conduct an intensive imaging survey for young galaxy clusters and proto-clusters up to z~5 based on rest-frame infrared light, so that we can reveal the "real" activity of galaxies at various epochs and various environments. This will enable us to reveal the star-formation and mass-assembly history in the early universe, as well the environmental effect on galaxy evolution.	In the early universe where the star forming activities reached a peak(z=1~2), and even more past era (z~5), we will observe clusters and large scale structures in the infrared band, to which the redshifted emitting energy shifts, with a sufficiently wide field of view. Then we may resolve the true galaxy star-formation & mass-assembly history along the time-axis and environmental axis. [moderate impact]	We will reveal the histories of cosmic star formation and mass assembly upto z~5. We will also perform much wider survey (corresponding to 300 Mpc) to detect the infrared galaxies' clusters which can never be discovered from the ground-based observations. [large impact]

Table 2　Scientific Objectives, Targets, & Success Criteria (1/3)

Scientific Objectives		Scienetific Targets	Full Success	Extra Success
Life Cycle of Interstellar Dust ・Origin of interstellar dust (Formation/Destruction) ・Grain Growth in Dense Molecular Clouds ・Interstellar Dust in External Galaxy	Dust formation scenario by massive stars are examined to explore the origin of interstellar dust in the early universe.	Observations of several (>5) dust-forming supernovae in nearby (<25Mpc) galaxies are required several times within 1-2 years after the explosion. We try to demonstrate the evolution of mid-infrared spectra of the supernova during the processes in which dust is newly condensed in the SN ejecta gas and then it is cooled down to the temperature of circumstellar pre-existing dust (~ a few hundred K). Based on those datasets, its composition, its size distribution and its total mass are obtained.	The mid-infrared spectral evolutions of several dust forming SNe within 25Mpc during an initial few years after the explosion are examined in order to estimate the composition and the accurate amount of newly formed dust by excluding the contribution of pre-existing dust. [moderate impact]	Mid-infrared spectra of statistically sufficient number of nearby SNe (<25Mpc) of various types at several epochs during an initial few years after the explosion are obtained. Based on those datasets, we try to examine the relation among the newly formed dust, its precursor molecules, and ejected gas around the SNe. We aim to constrain the physical conditions that are necessary for dust to condense in the ejecta of SNe.
	Dust formation scenario by low to intermediate mass stars are examined to explore the origin of dust contained in the Milky Way and in the current universe.	Spatially well-resolved observations of faint dust shells around ~30 low- to intermediate-mass evolved stars (e.g., AGB stars, planetary nebulae, novae etc) in the Milky Way and in the Magellanic clouds are required to investigate their mass-loss histories and the dust-formation processes. Mid- to far-infrared spectra of spatially-resolved molecular and dust shell are obtained to identify the constituents of the	The detailed structures of the melecular and dust shell around ~30 low- to intermediate mass evolved stars in the Milky Way and in the Magellanic Clouds are examined. The presense of PAH features illuminated by less energetic photons around C-rich AGB stars are inspected to identify the formation site as well as the formation processes of PAHs. [moderate impact]	We try to examine the relation among the circumstellar dust, precursor molecules, and ejected gas based on mid- to far-infrared imaging and medium- to high- resolution spectroscopy of statistically sufficient number of low-to intermediate-mass evolved stars in the Milky Way. The formation process of MOLsphere and the dust formation scenario by low- to intermediate-mass stars are demonstrated.
	Dust formation and grain growth in the cold dense molecular clouds are examined.	Mid- to Far-infrared spectroscopic observations of ~30 cold dense molecular clouds with embedded young stellar objects in the Milky Way are required to detect the infrared bands of iron sulphide grains and to demonstrate the link between the Glass with Embedded Metals and Sulfides (GEMS) in Interplanetary Dust Particles (IDPs) and the interstellar grains. The grain growth scenario in cold dense	The presense of 23.5, 34, 38, 44μm features carried by iron sulphieds are searched in the 20-45μm spectra of ~30 cold dense molecular clouds in which the enhanced depletion of sulpher to dust grains are suggested. Then we try to find out a conclusive link between the GEMS in IDPs and the dust synthesized in the cold dense clouds.	We aim to systematically understand the role of cold dense molecular clouds as the site of dust synthesis and/or the grain growth. In collaboration with ALMA project, observational evidence for the chemical systhesis of organic molecules on the surface of dust grains are detected. [large impact]
	Effects of supernovae on the material evolution are elucidated focusing on the formation and destruction of dust grains and on the energy supply process to the ISM	About 30 SNRs so far detected in the infrared as well as those detected in Objective #5 will be observed with Imaging spectroscopy in the mid-to far-infrared to investigate the composition/amount of formed dust, shock effects, and effects on the ISM (In total about 400 to 500 hours).	Spatially resolved images and spectra of ~30 SNRs in the Milky Way and in Magellanic Clouds are obtained in the mid-to far infrared. The composition and the amount of dust in the SNRs are examined. We try to understand how efficiently the dust formed around the SNe is destroyed by SN shocks or survives to become the interstellar dust. [moderate impact]	From the spatially resolved NIR, MIR & FIR images and spectra of SNRs the composition and the amount of dust in the SNRs are measured and examined by using larger number of samples in various physical conditions in external galaxies. By NIR spectroscopic mapping of young core-collapse SNRs in the Galaxy, we will understand the SN explosive nucleosynthesis and explosion process
	the physical processing and chemical evolution of the ISM in galactic scales are examined in view of material circulation within nearby galaxies.	By mid- to far-infrared imaging spectroscopy (600 hrs in total), we spectrally decompose and spatially resolve emission from the ISM in 50 nearby galaxies of our AKARI sample, to track galactic-scale material circulation from sources to sinks of the ISM in galaxies, which complements the objectives #1-#4.	Low-resolution spectral mapping observations covering from 5 to 210μm of nearby galaxies of various Hubble types with the size of 5-10 arcmin in diameter are carried out. In addition, Med.-resolution spectral mapping observations covering from 10 to 210μm of the central part of each galaxy are executed. Based on those datasets, behavior of infrared emission from ISM in various astrophysical conditions are systematically understood. [moderate impact]	New dust features in the primitive 25-60micron wavelength range are identified and the mid- to far-infrared spectral energy distribution (SED) is modeled in details taking account of the composition of dust and their size distribution. We try to demonstrate the life cycle of interstellar dust in external galaxies, including the escape of dust into the Halo or into the intergalactic space, and the destruction process by hot plasma in elliptical galaxies and in the SNRs.
	Structues and constituents of the Milky Way are illustlated in details and the life cycle of the interstellar medium in the Milky Way is examined on a galactic scale in terms of the activities of low-mass to massive stars	Imaging and spectroscopic survey observations of the galactic plane will be carried out (600hrs) to obtain the point source catalogue listing 10^9 sources, low-resolution spectral catalogue of 10^7 sources, and the diffuse line emission spectral maps. Long-term variables, red clump stars in the Milky Way are completely searched and their effects on the evolution of interstellar medium are examined	The structures of the Milky Way in terms of the stellar distributions on a galactic scale are investigated. Especially, long-term variables and red clump stars are especially focused and are fully searched to find new Galactic structures and to understand thier contribution to the chemical evolution of interstellar medium. [moderate impact]	We try to detect the unknown Galactic structures in terms of the stellar distribution and to search for objects with unknown type of spectral energy distribution. [large impact]

Table 2(cont.) Scientific Objectives, Targets, & Success Criteria (2/3)

Scientific Objectives		Scienetific Targets	Full Success	Extra Success
Studies of Exoplanets and Solar Systems ・protoplanetary disks (gas, dust, structure) ・evoled systems (debris disks, gas-giant planets, solar-system small bodies)	To understand the diversity of the planetary systems, we will attempt to directly detect exoplanets and to measure their atmospheric composition in the infrared wavelengths.	With the planet/star contrast ratio of 10^{-6} or better, we will directly detect gas exoplanets, and perform their spectroscopic observations to clarify the composition of the atmosphere. Comparison with the results on our Solar System planets enables us to reveal the diversity of the planetary systems. With the spectroscopic observations utilizing the transit method, we will try to detect the atmosphere of giant earth-like planets. We will also apply the same approach to gas giant planets for detailed studies of their atmosphere.	With the spectroscopic observations utilizing the transit method, we will detect the atmosphere of giant earth-like planets. We will also apply the same approach to gas giant planets and study their atmosphere in detail. [moderate impact]	With the planet/star contrast ratio of 10-5 or better, we will observe 100 targets to search for gas-giant exoplanets, and will directly perform their spectroscopic observations to clarify the composition of the atmosphere. [large impact]
	We will reveal the formation mechanism of gas giant planets and initial condition of terrestrial planet formation, by observing the dissipation of gas and geometrical evolution in planet-forming regions.	With unprecendented sensitivity at 20-40 um, we will survey for emission lines which could be (or are) associated with warm gas (100-1000 K) in protoplanetary disks. Using lines associated with disks, we will measure the amount of gas and how it varies with stellar mass and ages. We will elucidate the geometric, physical and chemical structure of proto-planetary disks by measuring the motion of gas with high-dispersion infrared spectroscopy.	We will survey for emission lines (molecules, atoms, and ions) which could be formed in protoplanetary disks, revealing their origins. Using lines associated with disks, we will measure the amount of gas and how it varies with stellar mass and ages. We will elucidate the structure & physical/chemical conditions of proto-planetary disks by measuring the motion of bright emission lines with high-dispersion infrared spectroscopy.	Using lines associated with disks, we will measure the amount of gas and the dissipation of gas and their structural evolution in planet-forming. We will also observe disks at various evolutionary phases to study the changes of disk structures and physical and chemical states. Dependence on stellar masses and binarity will be studied as well. [large impact]
	We reveal the similarity or diversity of extrasolar systems by observing a number of debris disks, which are much more easily observable than exoplanets.	With the help of 3 times or higher spatial resolution and 10 times or higher sensitivity than AKARI, we will detect a number of disks whose amount of dust of even comparable to our solar system, leading us to understand relationship with planetary systems observed using the other methods.	We will observe a number of (~100))disks around nearby (<20pc) stars whose amount of dust is 10 times as large as our solar system, and bright disks with distance up to 1kpc. [moderate impact]	We will detect a number of disks around nearby (<20pc) stars whose amount of dust is comparable to our solar system, and study the relationship with metalicity for dusty disks. [large impact]
	We will reveal the role of ice for planet formation, and how the elements for originating and sustaining life could be supplied to terrestrial protoplanets.	We will apply high-contrast IR corpnagraphy to protoplanetary disks and debris disks, observe their structures, and understand their relationship for disk evolution. Through infrared spectroscopic observations with 3 times or higher spatial resolution than AKARI, we will reveal distribution and physical state of solid materials, particularly ice, in proto-planetary disks and dust disks in the main-sequence stars.	Through infrared spectroscopic observations with 3 times or higher spatial resolution than AKARI, we will observe 100 protoplanetary disks and debris disks. [moderate impact]	We will observe protoplanetary disks and debris disks around main-sequence stars up to 150pc including several star forming regions. [large impact]
	In order to reveal the whole picture of the solar system, we will survey for physical information of primordial objects in the solar system.	With the help of 10 times or even higher sensitivity than AKARI, we will survey for FIR emission asociated with a number of primitive objects in the solar system, and conduct systematic studies of their albedo, size, and thermal inertia.	We will observe thermal FIR emission of primitive objects up to the distance of 30-50 AU, and radius of <100 km s-1. This will reveal the correlation between their oribits and physical parameters, thereby allowing us to understand the evolutional histrory of outter solar system. [moderate impact]	We will conduct systematic FIR spectroscopy of the bright targets and reveal their surface composition of ice and minerals. [large impact]

Minimum Success
Among the above cliteria, to achieve at least two [moderate] impact scientific goals.

Table 2(cont.) Scientific Objectives, Targets, & Success Criteria (3/3)

Scientific Targets	Core Wavelength region	Telescope temperature	Diameter of Telescope (collecting power)	Diameter of Telescope (image resolution; WFE)	Minimum Sensitivity	Wavelength Resolution (lambda/delta lambda)	Field of view	Observing time	Commission of Observations	Data generation rate (Average, peak)	Key observing instrumets
We will search for redshifted ionized H lines, H2 lines and dust emission band (z>4) from active star-forming galaxies at z>4 with mid-& far-IR spectroscopy. We also search for star-forming galaxies at z>4 by using flux magnification due to cluster gravitational lens, and dust-cocooned Gamma Ray Bursts at z>4.	[full success] MIR&FIR [extra success] NIR	[Full Success] 6.0K or below [Extra Success] 5.5K or below	3m class or larger	3m class or larger	1E-20 W/m2	[full success] SAFARI > 700 [extra success] BLISS > 700	SAFARI: >2arcmin MIRACLE: >6 arcmin	2 year or more	JWST, TMT	Average < 1Mbps peak 2Mbps	[full success] MIRACLE SAFARI [extra success] BLISS FPC-S
We will resolve the cosmic far-infrared background light into individual far-infrared objects with 3 times or more higher spatial resolution than that of AKARI. We then evaluate far-infrared background residual brightness and its fluctuations after removal of the individual objects, and reveal its origin through detailed analysis such as multi-wavelength correlation.	Full success: FIR Extra success: NIR	[Full Success] 6.0K or below [Extra Success] 5.5K or below	2.5m or larger	2.5m or larger	[full success] 100uJy @ 70um [extra success] 50uJy@70um	several (imaging) SAFARI > 700	> 1 arcmin	one year or more	ALMA	Average <4Mbps Peak TBD	[full success] MIRACLE SAFARI [extra success] BLISS FPC-S
We will reveal interstellar environment and dust emission characteristics of high-redshift galaxies out to z~3 through PAH emission as well as atomic and molecular emission lines with broad-band mid- & far-IR moderate resolution spectroscopy. These observations allow us to reveal the physical & chemical conditions of dusty galaxies in the early universe (up to 9 Gyr ago) with precise correction for dust attenuation.	MIR and FIR	[Full Success] 6.0K or below [Extra Success] 5.5K or below	3m class or larger	2.5m or larger	[full success] 1E-19 W/m2 [extra success] 1E-20 W/m2	100 & >700 (spectr.)	> 1 arcmin	one year or more	JWST, TMT. ALM	Average <4Mbps Peak TBD	[full success] MIRACLE MIRMES SAFARI [extra success] BLISS
We will make infrared imaging & spectroscopic observations of statistically meaningful number of candidates in search for the forming super-massive black holes (SMBHs), that can not be observed easily in other methods due to the obscuration of dust, from the present to the early universe. Supplementing these results with the results of observations for the galaxy formation history, we will understand the role of SMBHs in the galaxy evolution.	MIR and FIR	6.0K or below	2.5m or larger for "full success" 3m class or larger for "extra success"	3m class or larger	20uJy @20um	Iimaging: several Spectr.: >100	> 1 arcmin	one year or more	JWST, TMT, IXO	Ave.: 0.33-1.6Mbps Peak: 3.94Mbps	MIRACLE MIRMES SAFARI
We will conduct an intensive imaging survey for young galaxy clusters and proto-clusters up to z~5 based on rest-frame infrared light, so that we can reveal the "real" activity of galaxies at various epochs and various environments. This will enable us to reveal the star-formation and mass-assembly history in the early universe, as well the environmental effect on galaxy evolution.	MIR and FIR	[Full Success] 6.0K or below [Extra Success] 5.5K or below	3m class or larger	3m class or larger	MIR: 5uJy for "full success" 1uJy for "extra success" FIR: 100uJy for "full success" 50uJy for "extra success"	several (imaging)	> 4 arcmin for "full success" > 6 arcmin for "extra success"	one year or more	JWST, TMT	Average <4Mbps Peak TBD	MIRACLE SAFARI

Table 3 Mission Requirements　(in terms of specification requirements) (1/3)

Scientific Targets	Core Wavelength region	Telescope temperature	Diameter of Telescope (collecting power)	Diameter of Telescope (image resolution; WFE)	Minimum Sensitivity	Wavelength Resolution (lambda/delta lambda)	Field of view	Observing time	Commission of Observations	Data generation rate （Average, peak）	Key observing instruments
Observations of several (>5) dust-forming supernovae in nearby (<25Mpc) galaxies are required several times within 1-2 years after the explosion. Changings in mid-infrared spectra of the supernova during the processes in which the dust is newly condensed in the SN ejecta gas and then it is cooled down to the temperature of circumstellar pre-existing dust (~ a few hundred K) are examined to specify its composition, its size distribution and its total mass.	MIR & FIR (4-200um)	< 6K	3m class or larger	3m class or larger	MIRACLE: 10 times better than IRS SL&LL MIRMES: 10 times better than IRS SH&LH SAFARI: 100 tiimes better than PACS	MIRACLE:>100 MIRMES:>1000 SAFARI:>1000	MIRACLE: >1 arcmin MIRMES: ~10 arcsec SAFARI: >1 arcmin	>2 years（taking account of the SN explosion rate)	Independent of JWST. SPICA's wavelength range, especially from 25um to 60um is unique.	Ave.: <500Kbps Peak: 2Mbps	MIRACLE MIRMES SAFARI
Spatially well-resolved observations of faint dust shells around ~30 low- to intermediate-mass evolved stars (e.g., AGB stars, planetary nebulae, novae etc) in the Milky Way and in the Magellanic clouds are required to investigate their mass-loss histories and the dust-formation processes. Mid- to far-infrared spectra of spatially-resolved molecular and dust shell are obtained to identify the constituents of the molecular/dust shells and the properties of dust formed in the mass-loss gas.	MIR & FIR (4-200um)	< 6K	2m class or larger	10um diffraction limit（starting wavelength of SPICA/MIRMES）	MIRACLE: 10 times better than IRS SL&LL MIRMES: 10 times better than IRS SH&LH SAFARI: 100 tiimes better than PACS	MIRACLE:>100 MIRMES:>600 MIRHES:>10000 SAFARI:>1000	MIRACLE: >1arcmin MIRMES: ~10arcsec MIRHES: ~a few arcsec SAFARI: >1 arcmin	>2 years (better than Herschel)	After the JWST. JWST results are used for target selections. SPICA's wavelength range, especially from 25um to 60um is unique.	Ave.: <2Mbps Peak: ~4Mbps	MIRACLE, MIRMES MIRHES, SAFARI
Mid- to Far-infrared spectroscopic observations of ~30 cold dense molecular clouds with embedded young stellar objects in the Milky Way are required to detect the infrared bands of iron sulphide grains and to demonstrate the link between the Glass with Embedded Metals and Sulfides (GEMS) in Interplanetary Dust Particles (IDPs) and the interstellar grains. Then the grain growth scenario in cold dense molecular clouds are explored.	MIR & FIR (4-200um)	< 6K	3m class or larger	3m or larger	MIRACLE: 10 times better than IRS SL&LL MIRMES: 10 times better than IRS SH&LH SAFARI: 100 tiimes better than PACS	MIRMES:>600 MIRHES>10000 SAFARI:>1000	MIRACLE: >1arcmin MIRMES: ~10 arcsec MIRHES:~a few arcsec SAFARI: >1 arcmin	>2 years (better than Herschel; so that we can check the data of Objective #3)	After the JWST. Results of JWST are used for target selections. SPICA's wavelength range, particularly from 25 to 60um is unique.	Ave.: <500Kbps Peak:2Mbps	MIRMES MIRHES SAFARI
About 30 SNRs so far detected in the infrared as well as those detected in Objective #5 will be observed with Imaging spectroscopy in the mid-to far-infrared to investigate the composition/amount of formed dust, shock effects, and effects on the ISM (In total about 400 to 500 hours).	[full success] MIR & FIR (4-200um) [extra success] NIR	< 6K	3m class or larger	10um diffraction limit（starting wavelength of SPICA/MIRMES）	MIRACLE: 10 times better than IRS SL&LL MIRMES: 10 times better than IRS SH&LH SAFARI: 100 tiimes better than PACS	MIRACLE: >100 MIRMES: >1000 SAFARI: two modes 100/2000	MIRACLE: >1arcmin MIRMES: ~10 arcsec, SAFARI: >1 arcmin	>2 years (better than Herschel; so that we can check the data of Objective #5)	After the JWST. Results of JWST are used for target selections. High sensitivity achieved by MIRMES and SAFARI is unique to detect emission from relatively cool dust in the SN ejecta.	Ave: <500Kbps Peak:2Mbps	[Full Success] MIRACLE MIRMES SAFARI [Extra Success] FPC-S
By mid- to far-infrared imaging spectroscopy (600 hrs in total), we spectrally decompose and spatially resolve emission from the ISM in 50 nearby galaxies of our AKARI sample, to track galactic-scale material circulation from sources to sinks of the ISM in galaxies, which complements the objectives #1-#4.	MIR & FIR (4-200um)	< 6K	3m class or larger	10um diffraction limit（starting wavelength of SPICA/MIRMES）	MIRACLE: 10 times better than IRS SL&LL MIRMES: 10 times better than IRS SH&LH SAFARI: 100 tiimes better than PACS	MIRACLE: >100 MIRMES: >1000 SAFARI: two modes 100/2000	MIRACLE: >5 arcmin MIRMES: ~10 arcsec SAFARI: >5 arcmin	>2 years (better than Herschel; 600hr corresponds to the length of the "Kingfish" program of Herschel)	After the JWST. JWST results are used for target selections. SPICA's wavelength range, especially from 25um to	Ave.: <500Kbps Peak: 2Mbps	MIRACLE MIRMES SAFARI
Imaging and spectroscopic survey observations of the galactic plane will be carried out (600hrs) to obtain the point source catalogue listing 10^9 sources, low-resolution spectral catalogue of 10^7 sources, and the diffuse line emission spectral maps. Long-term variables, red clump stars in the Milky Way are completely searched and their effects on the evolution of interstellar medium are examined	[full success] MIR [extra success] NIR	< 10K	2m class or larger	3m class or larger	FPC-S: 10 times better than Spitzer/IRAC MIRACLE: 10 times better than IRS SL&LL MIRACLE imaging : 10 times better than AKARI/IRC	MIRACLE:>100	MIRACLE: >5 arcmin FPC-S: >5 arcmin	>2 years (better than Herschel)	Independent of JWST.	Ave.: 2Mbps Peak: ~4Mbps	[full success] MIRACLE [extra success] FPC-S

Table 3(cont.) Mission Requirements　(in terms of specification requirements) (2/3)

Scientific Targets	Core Wavelength region	Telescope temperature	Diameter of Telescope (collecting power)	Diameter of Telescope (image resolution; WFE)	Minimum Sensitivity	Wavelength Resolution (lambda/delta lambda)	Field of view	Observing time	Commission of Observations	Data generation rate (Average, peak)	Key observing instruments
With the planet/star contrast ratio of 10^{-6} or better, we will directly detect gas exoplanets, and perform their spectroscopic observations to clarify the composition of the atmosphere. Comparison with the results on our Solar System planets enables us to reveal the diversity of the planetary systems. With the spectroscopic observations utilizing the transit method, we will try to detect the atmosphere of giant earth-like planets. We will also apply the same approach to gas giant planets for detailed studies of their atmosphere.	MIR	<=10K	>=3 m	>=3 m	1microJy @λ5microns	>200	> 0.5 arcmin	>=1yr	JWST, TMT, 8m-EXAO	Ave.: <500Kbps Peak: 2Mbps	[Full success] MIRMES MIRHES [Extra success] SCI
With unprecedented sensitivity at 20-40 um, we will survey for emission lines which could be (or are) associated with warm gas (100-1000 K) in protoplanetary disks. Using lines associated with disks, we will measure the amount of gas and how it varies with stellar mass and ages.	MIR, FIR	<=6.0K (full success) <=5.5K (extra success)	>=2 m	>=3 m	$10^{\wedge-19}$ W m^{-2}	>600	a few arcsec	>=1yr	TMT, ALMA	Ave.: <500Kbps Peak: 2Mbps	MIRMES MIRHES SAFARI
We will elucidate the geometric, physical and chemical structure of proto-planetary disks by measuring the motion of gas with high-dispersion infrared spectroscopy.	MIR, FIR	<=10K	>=3 m	>=3 m	$10^{\wedge-19}$ W m^{-2}	> 30,000	a few arcsec	>=1yr	TMT, ALMA	Ave.: <500Kbps Peak: 2Mbps	MIRHES
With the help of 3 times or higher spatial resolution and 10 times or higher sensitivity than AKARI, we will detect a number of disks whose amount of dust of even comparable to our solar system, leading us to understand relationship with planetary systems observed using the other methods.	MIR, FIR	<=6.0K (full success) <=5.5K (extra success)	>=2 m	>=3 m	10 microJy @ MIR	5	> 1.5 arcmin	>=1yr	JWST, ALMA	Ave.: <500Kbps Peak: 2Mbps	MIRACLE SAFARI
We will apply high-contrast IR coronagraphy to protoplanetary disks and debris disks, observe their structures, and understand their relationship for disk evolution.	MIR	<=10K	>=3 m	>=3 m	1microJy arcsec^{-2} @λ 5microns	100	> 0.5 arcmin	>=1yr	JWST, TMT	Ave.: <500Kbps Peak: 2Mbps	[Extra success] SCI
Through infrared spectroscopic observations with 3 times or higher spatial resolution than AKARI, We will reveal distribution and physical state of solid materials, particularly ice, in proto-planetary disks and dust disks in the main-sequence stars.	FIR, MIR	<=6.0K (full success) <=5.5K (extra success)	>=2 m	>=3 m	100microJy (<λ40 microns) 1 mJy (>λ40microns)	100	> 1 arcmin	>=1yr	JWST, TMT, ALM	Ave.: <500Kbps Peak: 2Mbps	MIRMES MIRACLE SAFARI
With the help of 10 times or even higher sensitivity than AKARI, we will survey for FIR emission asosciated with a number of primitive objects in the solar system, and conduct systematic studies of their albedo, size, and thermal inertia.	FIR, MIR	<=6.0K (full success) <=5.5K (extra success)	>=3 m	—	50-100 microJy (Photometry@FIR) 1 mJy (Spectroscopy@FIR)	5-100	> 1 arcmin	>=1yr	JWST, TMT	Ave.: <500Kbps Peak: 2Mbps	SAFARI

Table 3(cont.) Mission Requirements (in terms of specification requirements) (3/3)