

# A NASA-LED US CONTRIBUTION TO THE ESA/JAXA SPICA MISSION

*Unveiling the dust obscured Universe*

**A submission to the 2020 Decadal Survey**

**Theme: Medium Class Space Mission**

**Contributions**

**Authors:**

**Contact: Asantha Cooray, UCI [acooray@uci.edu](mailto:acooray@uci.edu)**

Charles (Matt) Bradford, JPL, US SAFARI lead

Michael Ressler, JPL, US SMI lead

Phil Appleton, IPAC

Lee Armus, IPAC

Cara Battersby, UConn

Ted Bergin, Michigan

Alberto Bolatto, Maryland

Caitlin Casey, UT Austin

Ranga-Ram Chary, IPAC

Christine Chen, STScI

Daniel Dale, Wyoming

Darren Dowell, JPL

Eli Dwek, GSFC

Eiichi Egami, Arizona

Duncan Farrah, Hawaii

Carl Ferkinhoff, Winona

Paul Goldsmith, JPL

Uma Gorti, Ames

Frank Helmich, SRON/Univ. Groningen

George Helou, IPAC

Charles L.H. Hull, NAOJ/ALMA

Varsha Kulkarni, South Carolina

Meredith MacGregor, Carnegie

Matt Malkan, UCLA

Eric Murphy, NRAO

Klaus Pontoppidan, STScI

Alexandra Pope, UMass

George Rieke, Arizona

Annie Sajina, Tufts

J. D. Smith, Toledo

Luigi Spinoglio, Rome

Gordon Stacey, Cornell

Johannes Staguhn, JHU

Kate Su, Arizona

Amy Trangsrud, JPL

Pasquale Temi, Ames

Michael Werner, JPL

SPICA Europe and SPICA Japan endorsement  
statement is on Page 1.

## EXECUTIVE SUMMARY

**The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) will conduct sensitive observations of the Universe at mid- and far-infrared wavelengths. The current mission design is a telescope with a 2.5m primary mirror, mechanically-cooled to below 8K, and with three instruments providing spectroscopy, imaging, and polarimetry between 12 and 350  $\mu\text{m}$ . SPICA improves over the spectral line sensitivity of previous missions between 30 and 230  $\mu\text{m}$  by a factor of 50—100. SPICA is currently competing with two other missions in ESA's Medium-Class 5 competition and is under going a concurrent Phase A design study with JAXA as a major partner. A NASA-led contribution is proposed to further enhance SPICA's capabilities, broadening its scientific scope, and to allow US community access to key programs and general observing time.**

**SPICA Europe/Japan Joint Endorsement:** The SPICA Collaboration, represented by Peter Roelfsema (SRON/Groningen, SPICA collaboration lead and SAFARI PI), Hiroshi Shibai (JAXA/Osaka, SPICA/Japan PI) and Hidehiro Kaneda (JAXA/Nagoya, SMI PI), endorses the possibility, after ESA Medium Class 5 (M5) Phase A downselection in mid 2021, to consider the enhancements identified in this White Paper (Table 5) to SPICA and to add capabilities beyond the scope of the current M5 baseline proposal to ESA. It is recognized by the SPICA Collaboration that proposed enhancements, which are not needed to achieve the core objectives of the ESA M5 mission proposal, if implemented, would significantly increase the breadth as well as the scope of the SPICA science objectives. Such enhancements could be pursued and the astronomical community at large would get access to an infrared observatory that is richer in capabilities than the baseline M5 configuration. Finally, it is also recognized that the US astronomical community would get a higher level of access to the observatory.

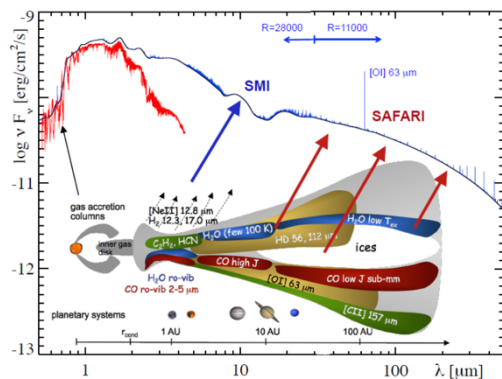
*How does the Universe work? How did we get here?* Answering these questions requires multi-wavelength measurements of the Universe, with sensitivity improvements that are orders of magnitude advancements over previous observations. The Universe remains mostly unexplored at the far-IR wavelengths. In particular, relative to the powerful near to mid-IR missions (e.g. upcoming JWST) and the ground-based millimeter-wave facilities (e.g. ALMA), far-IR wavelengths have been underserved scientifically because they require a space-borne observatory above the Earth's atmosphere, and for optimal sensitivity, a large, actively-cooled telescope.

A revolutionary advance in the far-IR is forthcoming with SPICA, an ESA-led mission with substantial JAXA participation now in Phase-A studies at both ESA and JAXA. Within ESA, SPICA is part of the Medium Class-5 (M5) mission competition, with a cost cap of 550M Euros. The final down-selection among the three M5 candidates (SPICA, EnVision to Venus, Theseus for gamma-ray transients) now in Phase A studies is expected in Summer 2021. These studies are required to have their Phase-A review documentation, including potential partner contributions, ready by February 2021. With a launch date in 2032, the baseline design is a science mission that will last a total of three years, with a design goal of five years. SPICA science program will be a combination of instrument teams' guaranteed time, open-time key projects, and open-time general observing campaigns. SPICA is expected to be  $> 85\%$  efficient (i.e., time spent on collecting science photons), comparable to *Herschel* & *Spitzer* that were 90% efficient.

SPICA will unveil the obscured universe with powerful spectroscopic probes in the mid- and far-infrared that free stream through galaxies' bulk regardless of dust. As is now well-known,

Table 1: Key scientific drivers for SPICA (as outlined by the ESA-led SPICA study)			
NASA Goal	How did we get here?	How does the universe work?	How did we get here?
<b>SPICA Science Goals</b>	<b>Understand the evolution of planet-forming disks in our Galaxy.</b>	<b>Understand the key physical processes that govern the star-formation activity in galaxies.</b>	<b>Understand the role of magnetic fields in Galactic star-formation.</b>
<b>SPICA Scientific Capabilities</b>	With sensitive, high-resolution spectroscopy at mid-IR and far-IR wavelengths, SPICA will study emission lines such as HD, H <sub>2</sub> , CO, H <sub>2</sub> O vapor, H <sub>2</sub> O ice features, and key dust features tracing the detailed mineralogy of refractory material in planet-forming disks.	With sensitive, high-resolution spectroscopy at mid-IR and far-IR wavelengths, SPICA will provide access to many diagnostic infrared emission lines that trace star-formation, super-massive blackholes, and feedback processes in galaxies.	By obtaining polarization maps of the Galactic ISM at 5 to 15 arcsecond scales, SPICA will determine the magnetic fields within filaments.
<b>SPICA Scientific Objectives</b>	1) Trace the gas, dust and ice evolution in planet-forming disks. 2) Establish how water – a key element for planet formation, and for the emergence of life – is brought to terrestrial planets. 3) Establish the “clock” for planet formation, by studying the dissipation and photoevaporation of gas.	1) Jointly measure the star-formation and active galactic nuclei (AGN) activity in galaxies, and study the co-evolution of AGN and galaxies with cosmic time. 2) Reveal the processes that regulate the baryon cycle and star-formation in galaxies. 3) Quantify the metal build-up in a galaxy population representing up to 80% of the total star-formation activity in the Universe.	Determine the relative role of turbulence, thermal processes, and radiation in the interstellar medium (ISM) of galaxies in regulating star-formation activity.

thanks to *Herschel* and *Spitzer*, as well as optical/UV measurements, that over the majority of cosmic time, dust obscures the conversion of gas into stars, the production of heavy elements, and the formation of planetary systems. Spectroscopy at far-IR wavelengths is the ideal tool for studying these transformations because it is both immune to extinction and directly measures the gas cooling that regulates these key processes. SPICA is designed to carry out spectroscopic surveys, individual point source studies at far-IR and wide-field mapping in mid-IR spectral lines, leading to key insights on the physical processes that govern star-formation and active galactic nuclei (AGN) in galaxies. SPICA also provides capabilities to solve some of the outstanding



**Figure 1. SPICA will uniquely detect both the gas phase and water ice reservoirs in proto-planetary and debris disks. SPICA will derive the mineral properties, grain temperatures, and iron content of planet-forming disks. SPICA will also measure the dissipation and photo-evaporation of the gas and constrain the lifetimes of proto-planetary disks.**

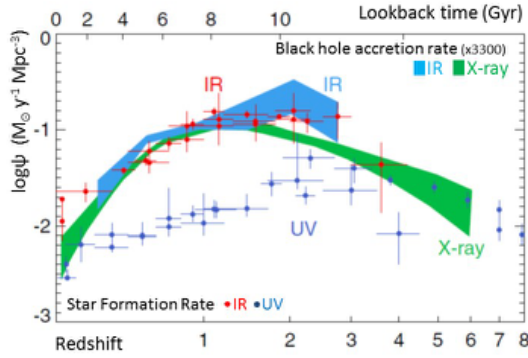
questions related to planet formation.

## 1. Key science goals and objectives

Table 1 outlines the key scientific goals of SPICA as currently considered within the SPICA study team led by ESA. We briefly discuss these objectives here.

**1.1 Disk evolution** The wavelength range of SPICA provides unique access to a large series of gas cooling lines from disks such as HD, H<sub>2</sub>, CO and water, to the far-IR water ice features, and to dust features tracing the detailed mineralogy of refractory material (Figure 1).

SPICA will study the mass evolution of the warm gas reservoir during the epoch of planet formation using HD/112 μm and OI/63 μm emission in large statistical samples. SPICA’s highest spectral-resolution modes will be used to quantify gas disk dispersal processes such as jets, winds and to link them to disk structures such as

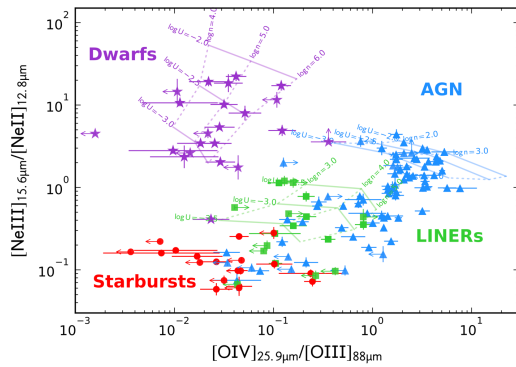


**Figure 2. Star Formation Rate densities in the FUV (blue points) and in the far-IR (red points).** Note that the bulk of the energy produced by stars and accreting black holes emerges in the infrared; in the IR many more objects than in the UV can be used to establishing this relation. The black hole accretion history from X-ray is shown in green shading) and from the IR in blue shading, scaled up by a factor of 3300, compared to the star-formation rate history. SPICA is able to study the dust-obscured evolution of galaxies during cosmic noon, through its ability to penetrate the dust and trace star-formation and blackhole growth.

as a result we will transition from discussing individual cases to establishing the general trends in planet forming systems.

Through broad band far-infrared spectroscopy, mineralogy of cold grains that are the dominant constituent of debris disks becomes possible. SPICA will follow the evolution of mineralogy from pristine phases in protoplanetary disks all the way to debris disks and link this to the composition of minor bodies, including asteroids, KBOs and comets in our own Solar System.

Dissipation and photoevaporation is a crucial process setting the lifetime of primordial gas in protoplanetary discs. At mid-infrared



**Figure 3. Observed line ratios of [NeIII]15μm/[NeII]12.8μm vs. [OIV]26μm/[OIII]88μm for AGN, LINER, starburst and dwarf galaxies in the local Universe compared to photoionization models.** These and other far-IR atomic fine structure lines provide a clear way to discriminate between the power sources in even the dustiest galaxies.

gaps, holes and asymmetries seen by ALMA, and scattered light imaging from the ground, HST, and JWST. SPICA will characterize late-stage debris disks and study the amount of gas and its composition and link them to its physical origin - leftover primordial gas versus comets/asteroids.

SPICA will also establish how water - a key element for planet formation, and for the emergence of life - is brought to planets like our own. By observing a wide range of water lines, it will trace the transition from the gaseous to the icy phase - the so-called snow-line. In particular, the long-wavelength far-IR lines connecting the ground state (e.g. 179 micron) are crucial because only these low-lying lines probe the vapor/ice transition. JWST, while very sensitive, will measure only the hot phase near the star. The water ice features at 40 and 60 μm provide crucial insight into the role and processing of water ice during the planet formation process (crystalline versus amorphous). Given SPICA's sensitivity such studies can be done for large samples of disks, and

protoplanetary discs. At mid-infrared wavelengths, using high resolution spectroscopy, SPICA will study how winds set the clock for planet formation. The key spectral signatures are with atomic and molecular wind tracers like [Ne II], [Fe II], H<sub>2</sub> and HD that are capable of measuring the dissipation and photoevaporation of the gas.

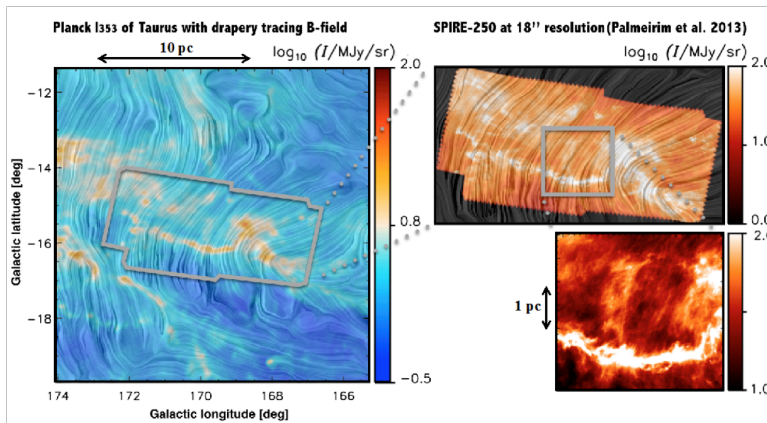
**1.2 Galaxy evolution** SPICA is designed to be a powerhouse for understanding galaxy evolution. It is now well established that the bulk of the star-formation and supermassive black hole accretion in galaxies took place around 10 billion years ago, at a redshift of  $z \sim 2$  during the peak epoch of galaxy and star-formation. Since most of the energy emitted by stars and supermassive black holes is absorbed by dust, understanding the physics of



star-formation and black hole growth at these epochs requires observations in the far-IR. The build-up of stars and supermassive black holes over cosmic time have roughly similar shapes (Figure 2), with a peak near  $z \sim 2$  and a sharp drop to the present epoch, suggesting that these processes are linked during the time when galaxies were rapidly growing, resulting in the tight correlation between the stellar and central black hole masses we see in the local Universe. SPICA will trace the co-evolution of AGNs and galaxies over the last 10 billion years of cosmic history, allowing the identification of even weak AGN activity in some of the most obscured galaxies (Figure 3).

SPICA will also reveal the processes that regulate the baryon cycle in galaxies, connecting stellar evolution with the reservoirs of gas and dust on scales ranging from giant molecular clouds to galaxy clusters. Gas accretion, outflows and energetic feedback play crucial roles in the evolution of galaxies.

The evolution of galaxies is regulated by energetic feedback from young stars, supernovae (SNe), and AGN, and the cycling of gas and dust; the underlying mechanisms are poorly understood but can be probed with far-IR spectroscopy. Most galaxies evolve through secular processes, such as smooth accretion of metal-poor gas, star formation, feedback, and the return of metal-enriched gas and dust into the interstellar medium (ISM) and circumgalactic medium



**Figure 5. SPICA will carry out sensitive polarization imaging of Milky Way filaments.** Herschel with angular resolutions of  $5''$  to  $10''$  showed ubiquitous galactic dust in thin filaments. Planck at  $3'$  to  $5'$  spatial resolution has observed large-scale magnetic fields that appear perpendicular to dense Herschel filaments. SPICA will allow capability to measure magnetic fields at  $5''$  to  $15''$  scales within filaments and bridge the gap between Herschel and Planck measurements, while also improving the overall sensitivity to regions of low polarized flux.

(CGM). Compression and cooling of the ISM enhances star formation, while outflows from stars, SNe and jets from AGN can heat the gas, destroy or modify the dust, and quench star formation. At  $z=0.5-2$ , SPICA is capable of mapping out the outflows and inflows of galaxies to determine the physical processes that govern how feedback helps shape a wide variety of galaxy properties and the connection between stellar and halo mass in galaxies. SPICA allows a broad range of important questions to be uniquely addressed in the far-IR.

As the third objective within this scientific goal (Table 1) SPICA will quantify the metal build-up in a galaxy population representing up to 80% of the total history of star formation activity in the Universe. Metals play a major role in gas cooling, cloud collapse, and ultimately the formation of stars and planets. The metallicity in galaxies is determined by the cumulative effects of star formation, outflows, and accretion. By using rest-frame mid-IR spectral tracers unaffected by dust, SPICA will accurately measure the gas-phase metallicity in galaxies over a wide range in redshift. In luminous galaxies, the HI 7-6 recombination line at  $12.3\mu\text{m}$  can also be measured, allowing a direct determination of the abundances of neon, sulfur, nitrogen, and oxygen.

**Table 2. Example SPICA Open-Time Programs.** Example Open-Time Key Programs (OT-KP) and Open-Time General Observing (OT-GO) programs that can be completed by the broader astronomical community. The exact time allocations and other details to be worked out between JAXA, ESA and NASA, with the assumption of a NASA contribution to SPICA. We expect the programs to be chosen by a competitive time allocation process like those used for other flagship missions.

Science Objective	Astrophysical Tool	Measurements Proposed	SPICA Instrument and observing mode	Time required
<b>Example SPICA Observatory Open-Time Key Programs</b>				
Cosmic dawn rise of metals and dust	H <sub>2</sub> , [SII], [FeII] as key coolants of reionization.	$\sim 300$ spectra of 50 galaxies at $z < 10$	Grating mode point-source spectroscopy.	1000 hours
Physical properties of rare sources	[OIV], [OI], [NII], [NeIII], [NeII] lines; PAH for hot dust emission.	20 deg <sup>2</sup> wide-field down to a sensitivity of $10^{11} L_{\odot}$ at $z=2$	Grating mode scan mapping	1000 hours
			SMI/LR+MR	1000 hours
ISM conditions of the Milky-Way	Spectral data cube of Milky Way disk	+/- 1 deg 3D map of full Galactic plane	Grating-mode scan mapping	3000 hours
Exo-Zodiacal clouds	Photometric and spectroscopy in mid-IR	1000 stars at $d < 20$ pc	SMI/CAM and SMI/LR	3000 hours
Direct Collapse black holes	Time-variability in a wide area photometric survey	100 deg <sup>2</sup> maps in 1 month cadence	SMI/CAM	2000 hours
Galactic Polarization and Magnetic Fields	Polarization maps of star-forming regions	1-10 deg <sup>2</sup> maps of selected SF regions	B-Bop	500 hours
<b>Total observing time proposed for OT-KP program (of 11,000 hours total expected)</b>				<b>11,500 hours</b>
<b>Example SPICA Observatory Open-Time General Observing</b>				
Various	Follow-up studies in mid and far-infrared of targets from JWST & WFIRST	Various, imaging and spectroscopy	SAFARI Grating/FTS mode mapping/spectroscopy	Various
			SMI/CAM/LR/MR/HR	

**1.3 Polarization in Filaments with SPICA** Understanding the star-formation processes in the ISM is vital to the study of evolution of galaxies. Yet a number of fundamental issues remain to be solved. The onset trigger is crucial for our understanding of star-formation activity. Magnetic fields and turbulence have energy densities similar to those of thermal processes and radiation in the ISM, and they are important agents in the formation of structure in the ISM.

*Herschel* and Planck findings have established a “filamentary paradigm” for star-formation, in which both magnetic field and turbulence dissipation play critical roles in the onset of star-formation, as material accretes to form filaments along magnetic field lines and dissipate their energy via radiative shocks to form first hydrostatic cores, followed by Class 0 protostar. SPICA will obtain high spatial resolution polarimetric observations and test existing models of star-formation by virtue of its efficient polarimetry in the far-IR and its highly sensitive spectroscopy from mid-IR to far-IR.

## 2. US scientific community access to SPICA

Table 2 highlights the potential for large open-time programs with SPICA. Such programs would span a wide range of topics, from large legacy-style key programs to follow-up of exciting JWST and WFIRST discoveries.

While exact details are to be established, SPICA will likely follow the ISO and *Herschel* examples, and have a significant fraction of the science time open competed. As a general observatory, the observing time will include community-led programs through guest observer

Table 3: <i>Herschel</i> Observing Time Allocations (hours)		
Category	Total time	US PI-led Time
Instrument GTOs	6796	400
Open time Key Programs	5378	1609
GO Open Time 1	6577	2824
GO Open Time 2	7590	2836

US PI-led is based on the listed PI's affiliation. Does not take in to account institutional changes. This should only be used as a guidance. Statistics miss programs that had active Co-PIs and Co-Is from US. GO OT1 & 2 includes Priority 1 and 2 selections.

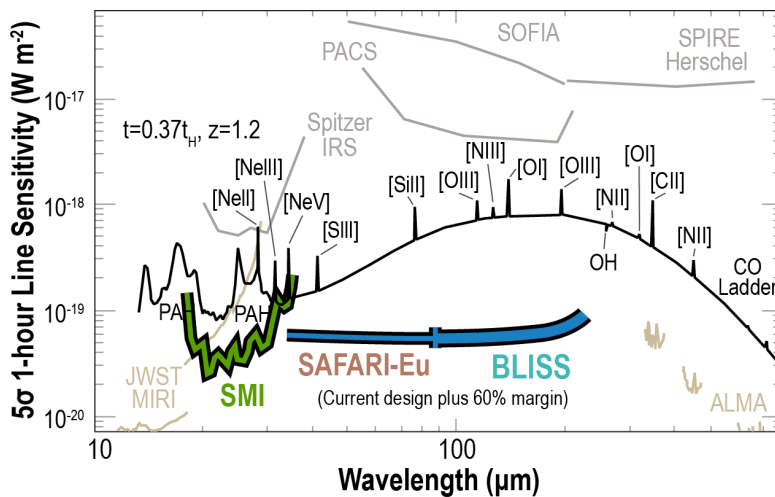
Table 4. SPICA Mission Parameters	
Wavelength	12-230 $\mu\text{m}$
Aperture diam	2.5m
Aperture temp	< 8K reqt; 6.5K goal
Cooling	V-groove passive + JAXA mechanical coolers for 25K, 4K, 1.7K stages
Pointing	0.44", $3\sigma$
Orbit	L2 halo
Lifetime	3 yrs (5 yrs goal)
Downlink rate	10 Mbps (peak), 3 Mbps ave
Launch	JAXA H3, 2032

(GO) programs. While the SPICA study team has publicly stated SPICA will follow the “open sky” policy with GO time decided by an international peer-review time allocation committee, that policy has yet to be finalized by the ESA management (at the level of the ESA Science Program Committee). There is also the possibility that SPICA observing time may end up following a structure like ALMA time allocations where the total time is divided to participating countries based on a pre-agreed formula.

In addition to GO, key programs may occupy a fraction of the total observing time, similar to key programs that were selected for *Herschel*. The rest of the time will be instrument team’s GTO programs.

Those will likely carry out some of the most driving science observations, given the freedom to design science programs that test the depths of the instrumental capabilities. US participation in instruments may be crucial to secure US community participation in both KP and GTO programs.

For reference, it is estimated that the US contribution to *Herschel* was at the level of 20% of the



**Figure 6.** With the actively-cooled telescope, the SMI and SAFARI spectrometers on SPICA approach the fundamental limits of shot noise from the astrophysical backgrounds. Table 4 provides more information on the SPICA mission. SPICA SMI curve is for medium resolution spectroscopy. SAFARI is at R=300 resolution sensitivity.

total cost of the mission. Those included detectors for the SPIRE instrument and key technologies for HIFI. Table 3 shows that US-based PIs led close to 29% of observing time on *Herschel*. A more useful analysis is with peer-reviewed publications that are based on *Herschel* data. By mid-2019, the total number of *Herschel*-related peer-reviewed publications was in excess of 2400, of which a total of more than 70% papers were US author-contributed. Regardless of the exact metric, it is clear that US had a substantial presence in scientific results from *Herschel*. US scientific

community also benefited from the NASA *Herschel* Science Center (NHSC) and GO science funds for the analysis and publication of *Herschel* data. We expect a similar impact from the US scientific community to SPICA-led science programs.

### 3. Technical Overview

**SPICA is 50—100 times more sensitive than prior far-IR missions.**



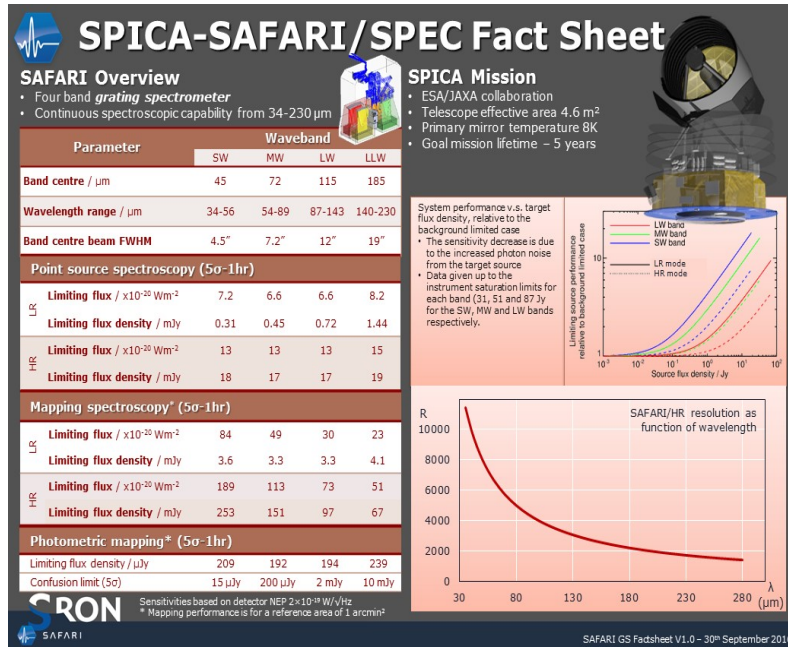


Figure 7. [The SAFARI fact sheet](#) showing specifications.

see below), and the launch vehicle. SPICA will feature revolutionary mid- and far-IR instrumentation, making use of the unprecedented sensitivity of a cryogenic telescope (Figure 6).

The first instrument is the **SAFARI** spectrometer covering 34 to 230  $\mu\text{m}$  (Figure 7), with 90 to 230  $\mu\text{m}$  wavelength coverage provided via a proposed technical contribution from US (BLISS; see Figure 6; Table 5; Section 4). With galaxy evolution science as the primary driver for the instrument requirements, SAFARI is optimized for sensitivity given the aperture size and telescope temperature at  $R \sim 300$  instantaneously over 34 to 230  $\mu\text{m}$ . A secondary driver is to study line profiles at higher spectral resolution, e.g. for the in-fall and outflow of matter due to AGNs. This

leads to the implementation of an additional high-resolution mode with a Martin Puplett interferometer for pre-dispersion of the signal.

With the grating-based design, the SAFARI sensitivity will be about  $7 \times 10^{-20} \text{ W m}^{-2}$  ( $5\sigma$ , 1hr at  $R \sim 300$ ; Figure 6), compatible with the sensitivity requirement dictated by scientific objectives. SAFARI is led in Europe by a consortium headed by SRON. The

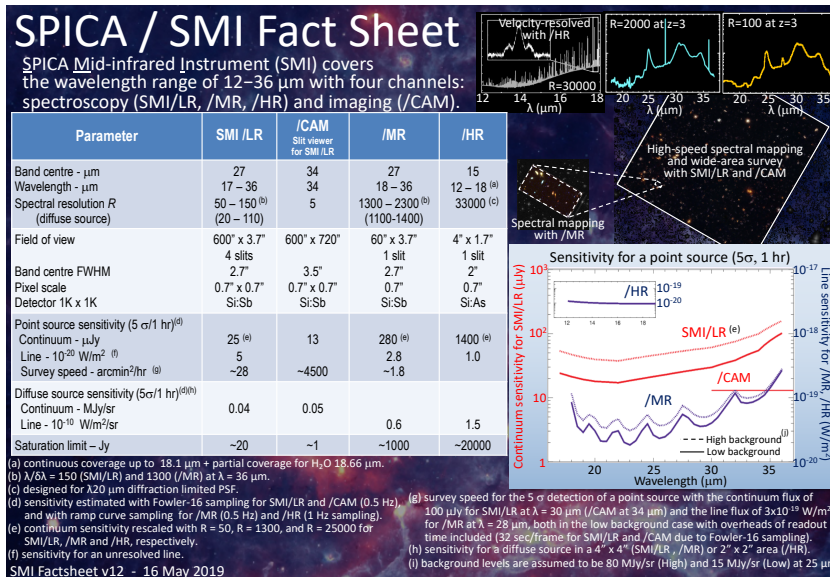


Figure 8. [The SMI fact sheet](#) showing specifications.



baseline plan for SAFARI includes a proposed US technical contribution to cover 90 to 230  $\mu\text{m}$  (BLISS; Figure 6, Table 5 and Section 4).

The second instrument is the JAXA-led **SPICA mid-IR instrument (SMI)**. It will offer imaging and spectroscopy from 12 to 36  $\mu\text{m}$  (Figure 8). SMI provides capabilities that complement JWST MIRI in 3 ways: 1) rapid wide-field mapping (broad band and spectroscopic); 2)  $R \sim 30,000$  spectroscopy with an immersion grating, compared to JWST maximum spectral resolving power  $R$  of 2600; and 3) extension to 36  $\mu\text{m}$  with antimony-doped silicon detector arrays, while MIRI is background limited above 13  $\mu\text{m}$ . The SMI mid-IR spectrometer/camera covers the wavelength range from 12 to 36  $\mu\text{m}$  with three separate channels: the low resolution (LR) spectroscopy at  $R=50-120$ , for the 17-36  $\mu\text{m}$  range, the mid-resolution (MR) spectroscopy at  $R=1300-2300$ , for 18-36  $\mu\text{m}$ , and the high-resolution (HR) spectroscopy at  $R = 28000$ , in the 12-18  $\mu\text{m}$  range. The SMI is composed of two main optics chains, one for LR and one for the MR/HR combination. For best performance sensitivity SMI requires US-based mid-IR detector technologies. This is also proposed as a technical contribution (Table 5; Section 4).

The third SPICA instrument is **B-Bop**, a continuum imager/polarimeter with three simultaneous imaging bands at 70 $\mu\text{m}$ , 200 $\mu\text{m}$ , and 350  $\mu\text{m}$ , led by an instrumental consortium based in France. B-Bop will enable magnetic field mapping over hundreds of parsecs in the Milky Way at 5'' to 15'' angular scales, filling the gap between Planck and ALMA. The polarimetric mapping requires a high dynamic range both in spatial scales and flux density, and a large instantaneous field of view, simultaneously in all wavelength bands. The adopted polarization-sensitive detector sensitivity of  $3 \times 10^{-18} \text{W}/\sqrt{\text{Hz}}$  can be achieved with existing detector technologies. There are no proposed plans for a US technical contribution to B-Bop.

### 3. Proposed US Contributions and Estimated Costs

**A NASA-led contribution to SPICA will result in access to open-time and key programs to the US astronomical community.**

Table 5 summarizes potential contributions to SPICA from US and the benefits to the US scientific community. A \$150M NASA instrument contribution to the then JAXA-led SPICA was recommended by the Astro2010 Decadal Survey, which never materialized. SPICA, if selected by ESA as the final M5 mission, presents an opportunity to address key scientific goals of the US astronomical community that cannot be addressed with SOFIA. After downselection in the ESA M5 process (mid 2021), there is a period prior to adoption in which NASA could participate in a joint study and offer augmented capabilities.

Table 5: A roadmap for NASA-led US participation in SPICA					
#	Proposed contribution	Rationale	Scientific benefit to the US community	Leadership of the US community	Estimated cost
Instrument level contributions to the baseline design (proposed MoO)					
1	<b>BLISS:</b> Two longest wavelength modules, including detectors and gratings and the readout system for SAFARI instrument.	This contribution is included as part of the baseline SAFARI instrument led by SRON as part of the ESA Phase A study. Within US this contribution is identified as BLISS with Charles (Matt) Bradford as the PI.	Provides 90-230 $\mu\text{m}$ spectroscopic capability for SAFARI (SAFARI-Eu is 34 to 90 $\mu\text{m}$ ); Figure 6 identifies US contribution as BLISS.	Maintains US leadership in sensitive far-IR detectors.	\$75M (Explore MoO cost cap; to be proposed as BLISS in 2019 SMEX).

Opportunities for strategic US involvement which enhances SPICA's scientific performance					
2	<b>SMI</b> detector contribution, flight-qualified, characterized detector modules for some or all channels.	Ensure the delivery of an optimized, low-power mid-IR detector capability to SPICA and provide an interface to the US commercial industry; based on <i>Spitzer</i> , WISE and JWST development and delivery experience.	SMI operates at the full capacity with a low dark and readout noise, allowing most sensitive observations in the mid-IR wavelengths. Guarantees SMI GTO access to the US community.	Maintains US leadership in sensitive mid-IR detectors.	\$30M-50M, depending on the scope of contribution.
3	<b>SAFARI &amp; BLISS-enhanced</b> (i) Increase maximum wavelength to 330 $\mu\text{m}$ and/or (ii) the number of sky pixels to increase the spectral survey speed.	Enhance SAFARI with strategic contribution outside of Explorer MoO constraints. Enhancements will require study after the ESA M5 downselection; opportunities include extending the wavelength coverage to 330 $\mu\text{m}$ , and/or increasing pixel count to increase mapping/survey speed.	Wavelength increase improves both low-redshift and high-redshift science in all key areas, bridging the gap with ALMA in specific important diagnostic features, e.g. OIII/88 studies for example.  Mapping speed increase allows blind spectral surveys, instead of SAFARI's current use as a targeted point source follow-up instrument.	Wavelength increase is a minimal change. Will require a study to determine pixel upscope is within mass and power resource margins.	\$100M, in addition to above #1.
4	<b>Extend the scientific mission duration</b> from minimum 3 years (5-year goal) to minimum 5 years with a 10-year design goal	A minimum 5-year mission (a goal of 10 years) is compatible with NASA-led missions such as JWST. The experience with <i>Herschel</i> is that a lifetime of 3 years was not adequate to cover the breadth of sciences offered by a capable observatory.	Longer duration allows more targets, including SAFARI follow-up studies of key targets found from SMI wide-area surveys, improving the scientific objectives that are now limited by the total integration times.  <i>Herschel</i> 3-year duration limited the SPIRE/PACS spectroscopic follow-up of bright, rare sources found with SPIRE wide surveys.	Contribution assumes US will take a substantial role to offset costs associated with longer duration requirements.	TBD
5	<b>Improve aperture temperature</b> from < 8 K to < 6.5K with 4.5K goal	Current study relies on of JAXA-led coolers that operate at 4.5K; the goal of 6.5K to a system at 4.5K is used as margin. 4.5K goal could be reached with the addition of another JAXA-led cooler to meet new requirements.	Cooling the telescope further improves the sensitivity at longer wavelengths, while the sensitivity below 150 $\mu\text{m}$ will not be impacted.  At 4.5 K, SPICA can access wavelengths > 350 $\mu\text{m}$ .	Contribution assumes US support to offset a cost item, allowing JAXA to add another cooler to account for the extra heat load.	TBD

Capitalizing on SPICA Hardware Investments					
6	NASA SPICA Science Center (NSSC)	For the benefit of the US scientific community, including management of data analysis funds. Follows the model of NASA <i>Herschel</i> Science Center with active participation from NSSC on the development of the SPICA data analysis pipeline.	Enables the US-led scientific studies through dedicated support to the US community on resources and tools. Activities: exposure time calculators and tools for proposal preparation and workshops; development of instrumental noise models; key modules for the overall data analysis pipeline; advocate for the US community needs within the EU/Japan SPICA Science Center & ESA/JAXA.	Increases scientific papers led by US-based authors. Also help with GO and OT-Key Program proposals, including tools to analyze early data.	\$50M

Item #1 (BLISS) is being pursued as a Mission of Opportunity in the 2019 SMEX competition. The contribution includes the two longest wavelength modules, covering 90-230  $\mu\text{m}$ , including grating spectrometers, for the SAFARI instrument. This NASA contribution is currently included as part of the baseline SAFARI design that will be presented to ESA as part of the Phase A study, with documents and commitments due in February 2021. The ESA down-selection is expected in Summer 2021. **We request Astro2020 endorsement of the proposed BLISS contribution to SPICA because Decadal input about the value to the US community is important for NASA program executives even for a MoO contribution.** An additional investment by NASA to SAFARI (Item #3) enhances its scientific performance; this would be undertaken in a concurrent study with the European team after the M5 competition.

A second modest contribution which also gives instrument-level US involvement and maintains technical skill base would be detector contributions to SPICA SMI. **We encourage Astro2020 to recommend an SMI technical contribution as another modest but high-payoff strategic contribution to SPICA.** This US contribution to the SMI (Item #2) will provide a number of the mid-IR detector modules. Following similar units for both WISE and JWST/MIRI, these would contain the detector arrays; a lightweight support structure to allow precision optical alignment and thermal isolation from rest of the instrument; and the housing which will provide both radiation-shielding as well as a bolt-on mechanical interface. These are equivalent to MIRI Focal Plane Modules, so considerable experience and heritage already exist in US.

In addition to hardware deliveries to SAFARI and SMI, these US contributions will also bring a wealth of knowledge about the characterization of mid and far-IR detectors as well as how to deal with their anomalies, ensuring the best quality science data with which to work. Based on the experience with *Spitzer*, *Herschel*, and JWST/MIRI, NASA participation would also allow US teams to contribute to both the operations planning and to the low-level data processing pipeline to mitigate instrumental/detector effects and methods to correct for them.

The costs in Table 5 were estimated based on a combination of heritage and experience. We do not estimate a cost for items #4 and #5 as those require a close interaction between NASA and ESA/JAXA. Item #4 on extending the mission duration is strongly encouraged. The three-year *Herschel* mission was barely able to follow-up rare sources discovered during the first two years sky maps with *Herschel*/SPIRE. This scenario will likely remain with the wide area SPICA/SMI mapping surveys yielding interesting sources for far-IR spectroscopy with SAFARI.

A NASA SPICA Science Center (item #6) is also highly desired to ensure a high-level science return to the US community as experienced with the NASA *Herschel* Science Center. **The Decadal Survey should consider relative merits of the participation options listed in Table 5 and recommend ones that would lead to full US community access to the Observatory.**