The SAFARI Imaging Spectrometer for the SPICA space observatory

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ABSTRACT

The Japanese SPace Infrared telescope for Cosmology and Astrophysics, SPICA, will provide astronomers with a long awaited new window on the universe. Having a large cold telescope cooled to only 6K above absolute zero, SPICA will provide a unique environment where instruments are limited only by the cosmic background itself. A consortium of European and Canadian institutes has been established to design and implement the SpicA FAR infrared Instrument SAFARI, an imaging spectrometer designed to fully exploit this extremely low far infrared background environment provided by the SPICA observatory.

SAFARI's large instantaneous field of view combined with the extremely sensitive Transition Edge Sensing detectors will allow astronomers to very efficiently map large areas of the sky in the far infrared – in a square degree survey of a 1000 hours many thousands of faint sources will be detected, and a very large fraction of these sources will be fully spectroscopically characterised by the instrument. Efficiently obtaining such a large number of complete spectra is essential to address several fundamental questions in current astrophysics: how do galaxies form and evolve over cosmic time?, what is the true nature of our own Milky Way?, and why and where do planets like those in our own solar system come into being?

Keywords: Infrared, spectroscopy, space astronomy

1. INTRODUCTION

In all fields of astronomy researchers are continuously advancing into the deeper reaches of the universe to understand its workings in more and more detail. Instrument builders are challenged to support this quest by further pushing the capability envelopes of the observatories, providing better spatial and spectral resolution as well as better sensitivity. In the infrared domain the limits on the sensitivity in modern observatories like JWST [1] and Herschel [2], are set largely by thermal emission from the telescope itself, especially for medium spectral resolution observations. In the ~20 to 500μm domain the thermal blackbody emission from the 45K (JWST) or 80K (Herschel) telescopes far outshine the celestial emission from the galactic cirrus clouds, the zodiacal light and the 3K cosmic microwave background. To reach a complete understanding of the formation and evolution of galaxies, stars and planets, we need a deep exploration of the cold universe, which can only be achieved with a truly cold telescope and detectors to match.

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It is this unique low background emission environment that the Japanese led ***SP**ace **I**nfrared telescope for **C**osmology and **A**strophysics* – **SPICA** – mission [3] (see Figure 1) promises in the early 2020s. With its extremely cold 6K mirror the telescope's thermal emission will be six orders of magnitude less than on JWST and Herschel, providing the environment that is essential to fully utilize the potential of detectors with extreme sensitivity, as only under these conditions they are not *'blinded by the telescope'*.

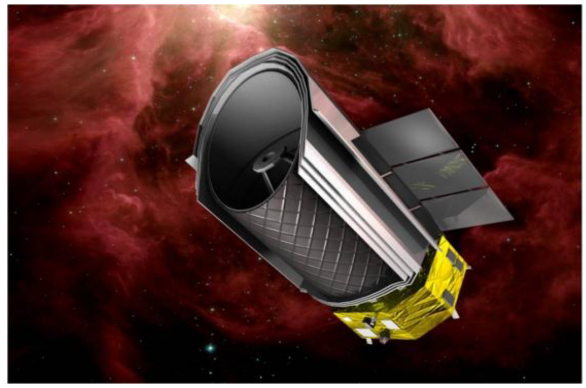

Figure 1 Artist impression of the SPICA satellite

The European SAFARI consortium, led by SRON, intends to provide one of SPICA's core science instruments; the versatile and ultrasensitive far infrared imaging spectrometer **SAFARI** – the ***S**pic**A** **FAR** infrared **I**nstrument*. This instrument will, in each integration, take complete 34-200μm spectra, spatially resolving the full 2'×2' field of view as illustrated in the left panel of Figure 2. With such spectroscopic imaging capability it will be possible to spectrally characterize all sources in the field in a very efficient manner. The gain obtained with such a major increase in sensitivity is illustrated in the right panel of Figure 2, showing the area covered by a full spatial and spectral survey (~1 deg^2, comparable to e.g. the Hubble Cosmos field). In such a field SAFARI will in 900 hours detect and spectroscopically identify all galaxies down to a luminosity of $\sim 10^{11}$ solar luminosities at a redshift z = 1 and $\sim 10^{12}$ solar luminosities at z = 2. In contrast, the Herschel-PACS spectrometer [4], the best instrument available to date, would require twice that time to reach the same sensitivity for only a single pointing - i,e, at best detect a few objects in a ~50"× 50" field. Clearly with such an increase in throughput SAFARI surveys will revolutionize our ability to spectroscopically explore the nature of thousands of objects.

This paper describes the SAFARI instrument and the status of its development. First a summary of the science goals driving the definition of the instrument is presented in section 2. An overview of the current baseline design is given in section 3, and section 4 concludes with the organization and status of the project.

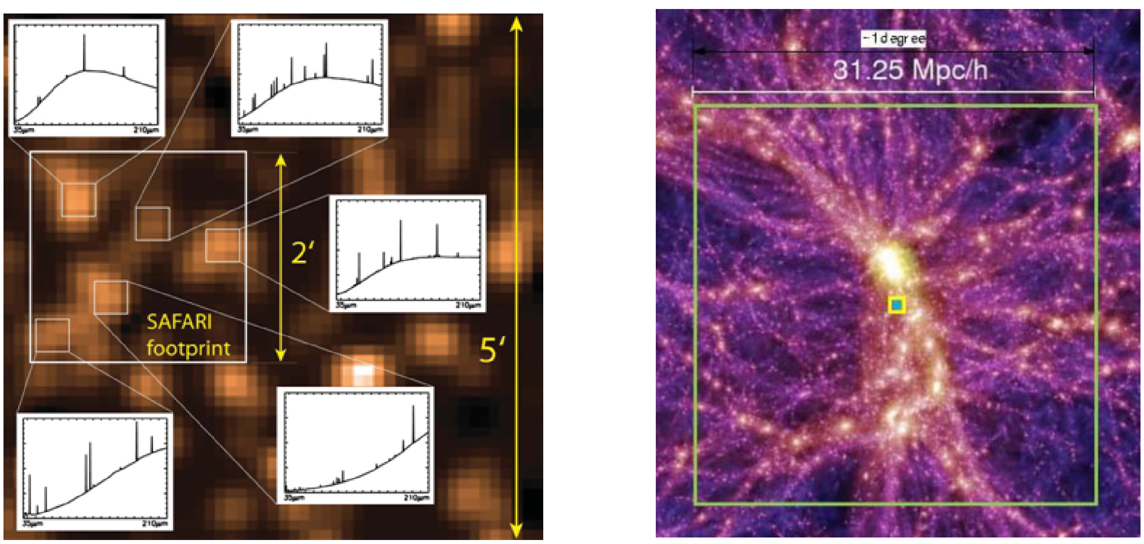

Figure 2 **Left panel**: A 5' × 5' region taken from an off-source part of a 250 μm ESA SPIRE publicity image, with an outline of the SAFARI 2'×2' field of view (credit: ESA and the SPIRE consortium). SAFARI will be able to obtain spectral information covering the full 34 - 210 μm range, in multiple sources, simultaneously in a single pointing**. Right panel:** Comparison of spectral surveys capabilities of SAFARI and Herschel-PACS superimposed on a realisation of the Millennium simulation at a redshift z~1.4. The footprints of the instantaneous spectroscopic field of view of PACS (blue dot) and SAFARI (yellow square) are indicated in the centre. The large green box shows the area covered by SAFARI in a 900 hour spectral survey down to 5×10^{-19} Wm^{-2}. In about twice this time PACS would reach the same sensitivity for a single pointing (blue box). In such a large area survey SAFARI will detect and characterise several thousand extragalactic sources.

2. THE SAFARI SCIENCE GOALS

Considering astronomy in its full breadth, three of the four major *Cosmic Vision* challenges for astrophysics can, in the context of SPICA and SAFARI, be reformulated as two fundamental "origins" questions: (1) how do stars and galaxies form and evolve over cosmic ages?, and (2) How does our solar system relate to other planetary systems and could life evolve elsewhere? The unique combination of high sensitivity, large field of view and wide spectral coverage in the far infrared make SAFARI the ideal facility to address these questions.

Galaxies near and far; understanding their formation and evolution

The universe is filled with galaxies like our own, each containing billions of stars, as shown by e.g. images taken with the Hubble Space Telescope [5]. Their physical properties such as mass, geometry, stellar and gas content, and chemical composition cover a huge range. Their distribution in space is far from homogeneous but follows that of dark matter, and as a result (clusters of) galaxies can be used as tracers of the structure of the universe. It has become clear that over cosmic time, from the very first generations of stars and stellar systems to the present-day universe, large changes in the nature of galaxies occur. Galaxies evolve due to the evolution of the stars they contain, by the accretion and expulsion of gas, and by merging with other galaxies (an example is shown in Figure 3) in the clusters they live in. When galaxies collide, a burst of star formation follows as a result of the compression of gas and dust clouds. At the centre of galaxies supermassive black holes form, whose mass scales with that of the host galaxy. These black holes accrete gas and as a result cause a tremendous cosmic firework by the accretion energy released.

Studies of galaxy evolution in a cosmological context have progressed greatly in the recent past, observationally establishing several results predicted from theory, such as the relation of black hole and galaxy masses [6]. Optical studies of the local massive galaxy population show that most, if not all, galaxy central bulges host massive relic black-holes which, in turn, suggests that all massive galaxies pass through a material-accreting, active galactic nucleus (AGN) phase [7]. The observed correlations between the masses of black holes at the centres of massive local galaxies and key properties of the host galaxies, such as their luminosities, dynamical masses, and velocity dispersions of their bulges are astonishing, given the vastly different scales that they involve [8][9][10][11]. The enormous difference between the Schwarzschild radius of a supermassive black hole (SMBH) and the characteristic radius of the stellar population in its host galaxy suggest that these relations are likely due to the coeval formation of the black hole and the bulge. The origin of these correlations cannot be fully explained by observations of local galaxies – both activities must be seeded at earlier epochs.

SAFARI observations will provide unique insight into basic questions of how galaxies form and evolve such as: What drives the evolution of the massive, dusty distant galaxy population, and what feedback/interplay exists between the physical processes of mass accretion and star formation? How and when do normal, quiescent galaxies such as our own

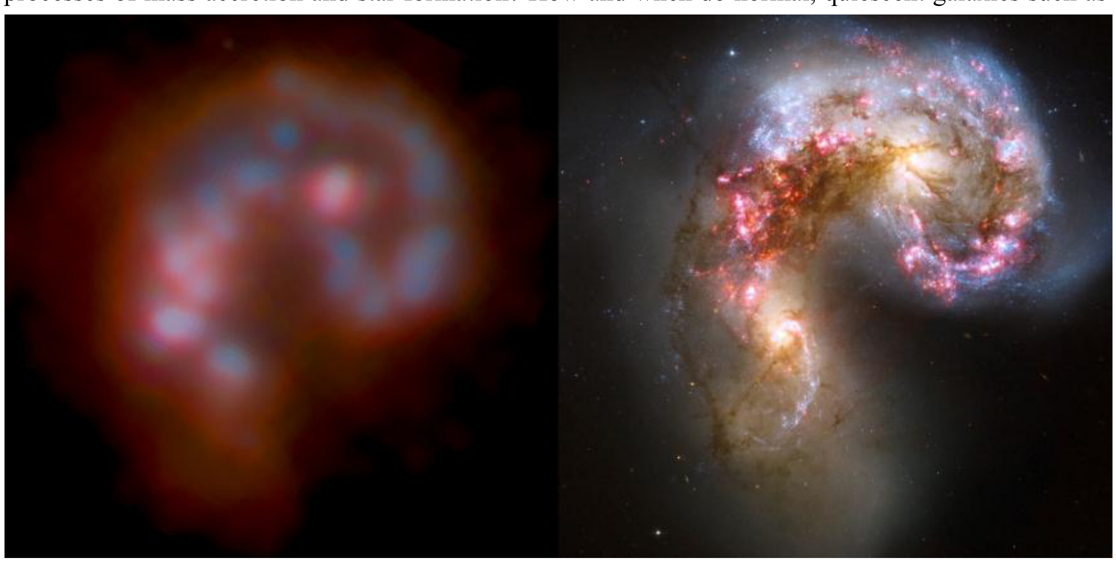

Figure 3 Herschel-PACS (left) and Hubble images of the colliding galaxy pair "the Antennae". Regions that are obscured in the Hubble image appear bright in the far-infrared. These are likely sites of massive star formation triggered by the collision. SAFARI will provide a full 34-210 μm spectrum at every pixel. (credit ESA/PACS/SHINING/U. Klaas & M. Nielbock, MPIA).

form, and how do they relate to (Ultra) Luminous Infrared Galaxies (ULIRGs) in which possibly many new massive stars are formed at the same time? How do galaxy evolution, star formation rate and supermassive black hole activity vary with environment and cosmological epoch?

Substantial progress in this area can only be made by making the transition from large-area photometric to large-area spectroscopic surveys in the mid to far infrared, which will be possible for the first time with SAFARI. This is because the mid and far infrared region plays host to a unique suite of diagnostic lines that trace the accretion and star formation, and probe the physical and chemical conditions in different regimes, from the supermassive black holes in the centres of galaxies to star-forming regions. SAFARI will be able to carry out blind spectroscopic surveys and detect multiple lines for many thousands of objects out to a redshift of z~3, when the universe was about 3.5 billion years old [12]. In comparison the current best instrument, Herschel-PACS, can only do this in the nearby universe out to z~1. SAFARI spectroscopic surveys will provide direct and unbiased information on the evolution of the large scale structure in the Universe from z~3 and the unprecedented possibility to investigate the impact of environment on galaxy formation and evolution as a function of redshift. This will lead to the first statistically unbiased determination of the co-evolution of star formation and mass accretion with cosmic time. Beyond z = 4 the high sensitivity of SAFARI will enable photometric surveys that will resolve more than 90% of the Cosmic Infrared Background (in comparison with the 50% that Herschel will achieve).

SAFARI will also observe Milky Way type galaxies in the far infrared out to z = 1, where the cosmic star formation rate peaks. For the first time, we will be able to piece together the story of the evolution of our own galaxy and to answer the question of whether we are in a "special place" in the cosmos. Additionally SAFARI will provide an unprecedentedly sensitive window into key aspects of the dust life-cycle both in the Milky Way and in nearby galaxies, from its formation in evolved stars, its evolution in the ISM, its processing in supernova-generated shock waves and massive stars, to its final incorporation into star forming cores and protoplanetary discs.

Putting our solar system into context

The last 15 years have seen a wave of new discoveries of exoplanets, planets orbiting other sun-like stars. Over 700 exoplanets have been confirmed so far [13], with their number increasing daily. The picture that emerges is that of a huge diversity in the properties of these planetary systems and of the planets in them. A key question is to understand this diversity and to determine if conditions in these planetary systems exist that are conducive to life as we know it. To answer these questions the formation of planetary systems must be studied and the formation history of our own solar system must be scrutinized in order to place it into context. Astrophysics is at an exciting crossroads where for the first time this can be done in a quantitative way, SPICA's mid-infrared instruments and SAFARI will make important contributions to this field.

There is strong evidence that planet formation takes place in the gas- and dust rich discs that surround all young sun-like stars. This disc is the remnant of the star formation process and is providing the matter for planet formation (see Figure 4). The proto-planetary discs evolve over a timescale of a few million years; during that period, the IR radiation which originates from the disk decreases as a function of age and gas accretion rate as inferred from different gas diagnostics. This is the critical intermediate stage when planetary formation is believed to take place, with dust particles colliding and growing to form larger bodies. Some discs have large inner dust holes on scales of several 10s of Astronomical Units (AU) which could be due to the formation of planets. The Spitzer Space Telescope [14] has provided us with a large sample of such discs based on their infrared emission; these discs are often referred to as "transitional discs"

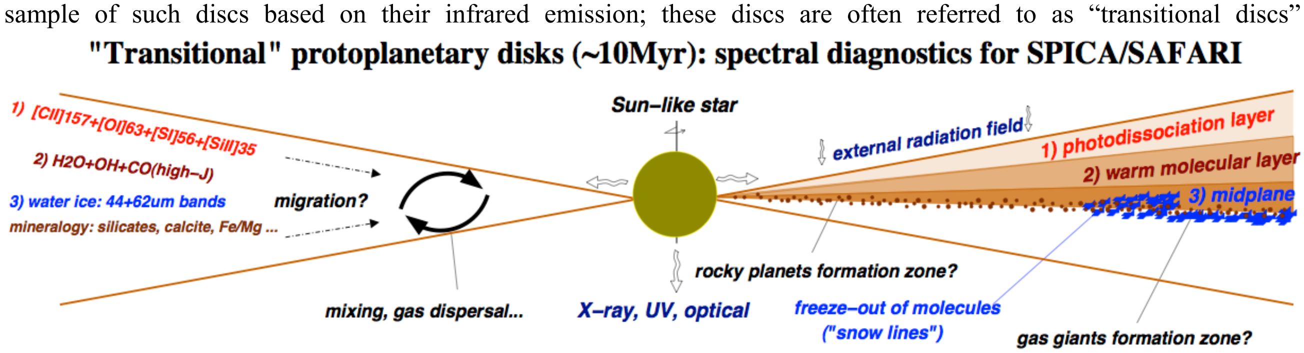

Figure 4 Diagram showing where radiation from a proto-planetary disc arises (at the time when planets assemble). As so much of this emission occurs at far-infrared wavelengths, SAFARI is essential to understanding the full picture of planetary formation and the primordial chemistry that leads to the emergence of life

[15][16][17]. Chemical complexity increases during this period of planet formation, but little is known about how this process evolves and how complex organic molecules are delivered to the protoplanets that form.

Discs with ages above 10 Myr are practically devoid of gas [18] and the dust in these older discs is generally not primordial but continuously generated "debris" from planetesimals and rocky body collisions. The smallest dust grains have, at this stage, either been dispersed or have coagulated into larger grains and the disc becomes very tenuous. These ***debris discs*** are thus more massive (and usually younger) analogues of our own asteroid (hot inner dust, T_d~200 K) and Kuiper belts (cool outer dust, T_d~60 K) so their study is vital to place the Solar System in a broader context. An example of such a disk around the nearby star Fomalhaut, as observed with PACS broadband photometry [19] is shown in Figure 5, SAFARI will image this kind of disk in all spectral lines between 34 and 210 µm.

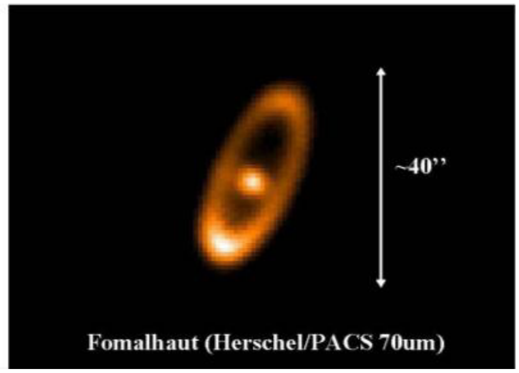

Figure 5 Herschel-PACS image of the debris ring surrounding the nearby star Fomalhaut [19]. The ring is caused by colliding rocky bodies, probably similar to those in the solar system Kuiper belt. A planet is believed to be responsible for stirring the debris ring.

By accessing key spectral diagnostic lines, SAFARI will provide a robust and multidisciplinary approach to determine the conditions for planetary system formation. This will include the detection for the first time of the most relevant species and mineral components in the gas and dust of hundreds of transitional protoplanetary discs at the time when planets form. We will also be able to trace the warm gas in the inner (< 30 AU) disc regions. SAFARI will study debris discs and make the very first unbiased survey of the presence of zodiacal clouds in thousands of exoplanetary systems around all stellar types. It will allow us to detect both the dust continuum emission and the brightest grain/ice bands as well as the brightest lines from any residual gas present in the disc. SAFARI will have the unique capability to observe water ice in all environments, and thus fully explore its impact on planetary formation and evolution and the emergence of habitable planets.

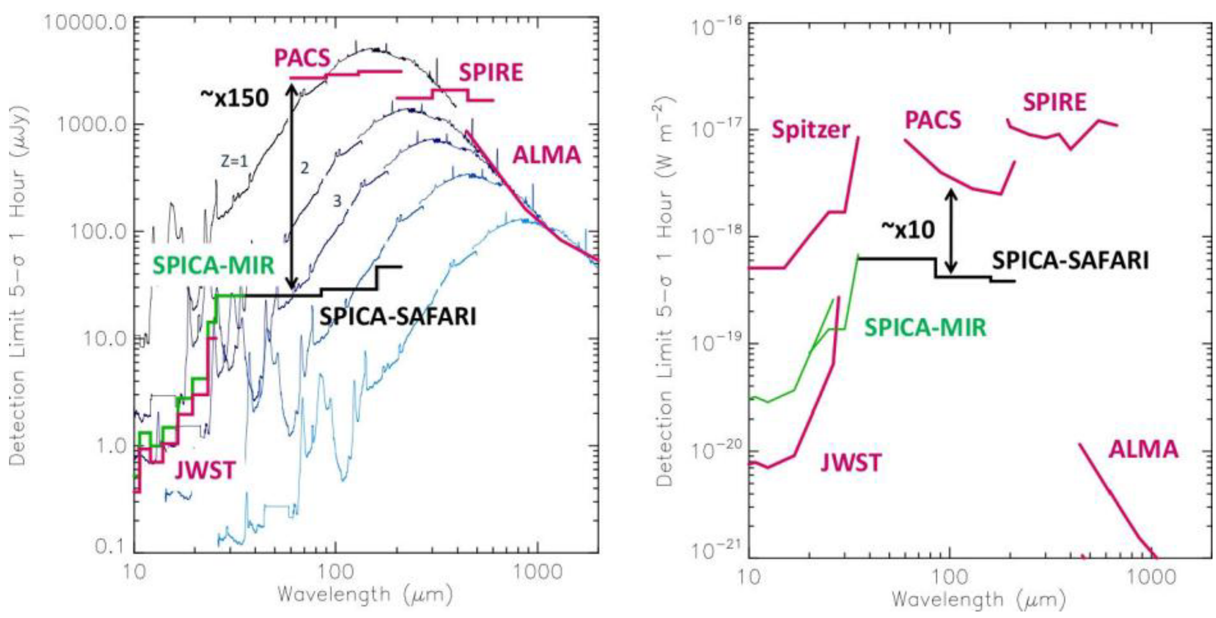

Figure 6 Left panel: Photometric performance expected for SPICA SAFARI (black) and SPICA mid infrared camera MCS (green), compared to Herschel, ALMA and JWST (red), for a point source (µJy, 5σ, 1 hour) using the goal sensitivity detectors on SPICA (Noise Equivalent Power, NEP=2×10^{-19} WHz$^{-1/2}$). Note the ~2 orders of magnitude increase in photometric sensitivity compared to Herschel-PACS. The Spectral Energy Distribution (SED) of the galaxy M82 as redshifted to z=1, 2, 3, 5 and 10 is shown for reference. Right panel: Spectroscopic performance expected for SPICA (black and green) compared to other facilities (red) for an unresolved line and point source (Wm^{-2}, 5σ, 1 hour). For comparison with ALMA 100 kms^{-1} resolution is assumed. Note that due to its low background level SPICA becomes more sensitive than JWST beyond 20µm.

The observation of circumstellar discs around distant stars at different evolutionary stages provides clues on how our planetary system was formed, from which materials, and how they were processed. However, in order to understand the observed diversity of extra-solar planetary systems, we also need to explain how our own Solar System emerged. Clearly these approaches complement each other and represent intimately and increasingly interconnected research fields. The study of the Solar System extends from the traditional investigation of the planets and their rings and moons, to the most recent characterisation of the different populations of primitive leftovers of their construction (comets, asteroids, Kuiper belt bodies, etc.). From an astrobiological point of view, the primitive bodies coming from the outer Solar System (with little or no chemical processing) could have delivered significant amounts of volatiles and chemical species to the inner rocky planets (e.g., water and organic matter) that are relevant for the habitability of such planets. The study of the enigmatic nature of the outer Solar System is very challenging because (1) at such large distances from the Sun, rocky and icy bodies are cold, below about 60K, such that their thermal emission peak is at far-infrared wavelengths that cannot be observed from the ground and (2) the far-infrared fluxes are very weak (a few mJy and below). The very sensitive SAFARI instrument with its broadband spectroscopic capabilities will provide a new perspective of the Solar System's outermost belts, the regions that hide a record of the earliest phases of the solar nebula. SAFARI will provide the means to quantify the composition and size distribution of hundreds of Kuiper belt objects: critical observational evidence for the models of Solar System formation. No other existing or planned facility will be able to carry out any of these observations.

3. INSTRUMENT OVERVIEW

To address the science needs identified above the foreseen SAFARI high throughput, sensitive imaging spectrometry capability is required. The main specifications for the instrument, given in Table 1 and Figure 6, have led to the concept of a Fourier Transform Spectrometer (FTS), able to provide continuous coverage in photometry and in spectroscopy over the desired wavelength range and over a 2'×2' field of view. To cover the full 34 to 210 μm wavelength range with adequate spatial and wavelength resolution the instrument employs three wavelength sub-bands each optimised to cover a single octave. Figure 6 illustrates the sensitivity requirements for the SAFARI bands as well as for the other SPICA instruments in comparison to other observatories. It is clear that with this performance SAFARI on the one hand will give a major step forward with respect to current observatories while on the other hand it will fill an important niche between the major future observatories.

Table 1 top level SAFARI specifications

Instantaneous field of view	2' × 2'
modes:	
Photometry	$\lambda/\Delta\lambda \sim 3$
Spectral Energy Distribution (SED) mode	$\lambda/\Delta\lambda \sim 150$ - 200
Spectroscopy	$\lambda/\Delta\lambda \sim 2000$
Instrument sensitivity 5σ-1hr	
line sensitivity	few × 10^{-19} W/√Hz
continuum sensitivity	<20 μJy
Wavelength bands:	
SW - Short Wave, 34-60 μm	43×43 bolometers
MW - Medium Wave, 60-110 μm	34×34 bolometers
LW - Long Wave, 110-210 μm	18×18 bolometers

The instrument utilizes a Mach-Zehnder interferometer as a means to obtain spectral information – a design used successfully in the Herschel SPIRE instrument [12], [21]. In such an interferometer, the incoming beam from the telescope is split over two symmetrical optical branches which each contain moveable mirrors. After being reflected off the moving mirrors the two beams are recombined again, and the combined beam is subsequently forwarded to the detectors. By moving the mirrors different path lengths along the two branches are obtained, and the resulting combined signal yields an interference pattern as function of the Optical Path length Delay (OPD). This interferogram corresponds to the Fourier transform of the incoming spectrum. By employing a detector array instead of a single pixel in the image plane, interferograms are obtained simultaneously for a large on-sky area. By applying a Fourier transform for each detector, a data cube of spectra for all pixels covering the instrument field of view is obtained. Observations obtained by

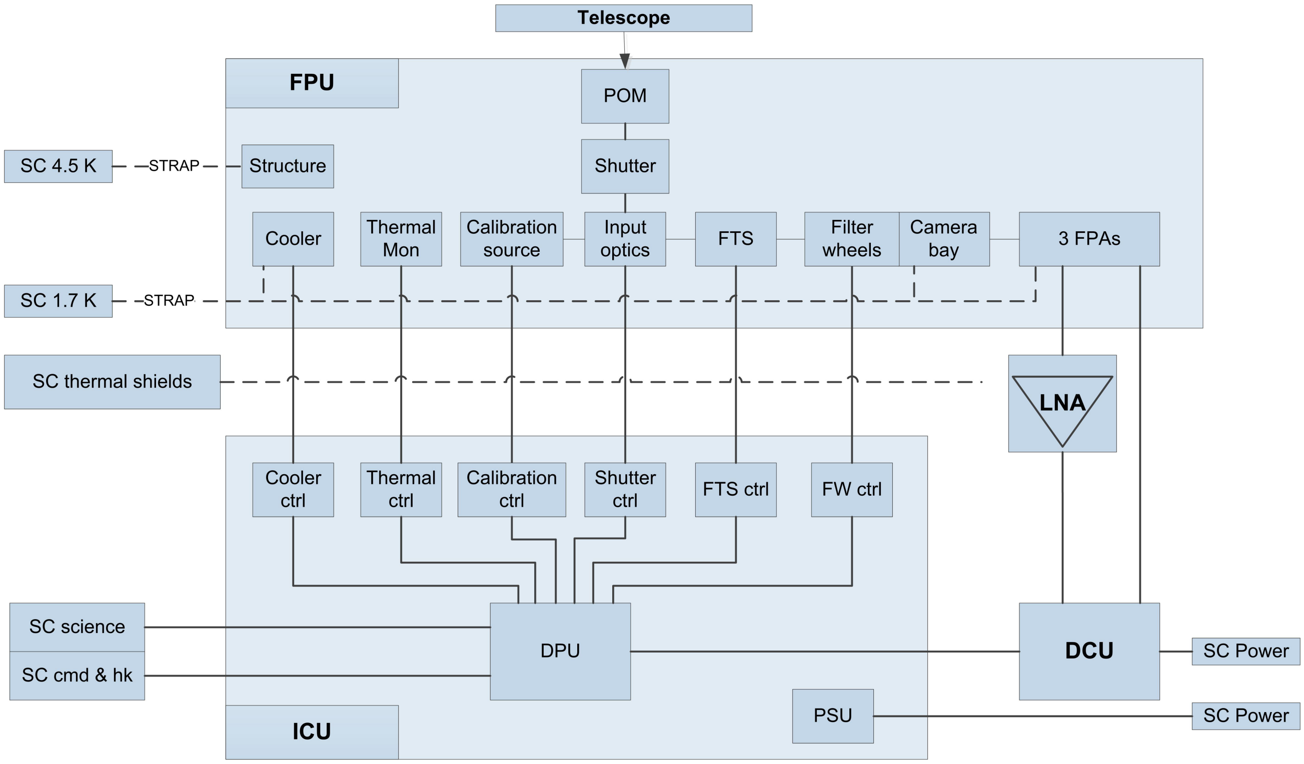

Figure 7 Functional breakdown of the SAFARI instrument. The top part corresponds to the 4.5 K Focal Plane Unit (FPU), in the lower part the warm electronics units are indicated with the Instrument Control Unit (ICU) and Detector Control Unit (DCU) as major components.

scanning the mirror of the Fourier Transform Spectrometer (FTS) over the full stroke yield spectra with the required resolution of R~2000 in the middle of the wavelength band. For lower resolution (SED mode) spectra a shorter scan is taken. Additionally the instrument can operate in a 3 band photometric mode in which the FTS is fixed at one end of its stroke. The three bands use separate large-format detector arrays, with smaller numbers of detectors for the longer wave bands. Since the telescope spatial resolution decreases towards longer wavelengths, fewer pixels are required to obtain full spatial sampling of the 2’×2’ field of view.

In Figure 7 a functional breakdown of the SAFARI instrument is given. The instrument is divided in two major components; the Focal Plane Unit (FPU) located on the SPICA cold Instrument Optical Bench (IOB) at 4.5 K (top part of the figure) and the warm electronics consisting of the Instrument Control Unit (ICU) and the Detector Control Unit (DCU) in the SPICA service module (SVM). The wiring harness to transport commanding and readout signals between the warm electronics and FPU is guided along the truss system between the SPICA SVM, and the telescope assembly and IOB. Unfortunately cable routing and thermal considerations give rise to a considerable harness length of over 10 meters. With the very low detector signal levels generated in the FPU, this long harness requires the use of additional amplification by means of low noise amplifiers, which are located at an intermediate temperature stage (at 136K), to boost the signal before transmitting it further along the harness towards the DCU.

3.1 The Focal Plane Unit

The Focal Plane Unit (see Figure 8) contains all the optics to carry and condition the infrared radiation, entering the SAFARI instrument from the SPICA Telescope Assembly at the Pick-Off Mirror (POM), through the Fourier Transform Spectrometer (FTS) system towards the sensors in the Focal Plane Assemblies (FPA, see below). In the input optics a beam splitter divides the incoming beam into the two Mach-Zehnder interferometer paths. The FTS mechanism at the heart of the interferometer consists of two sets of rooftop mirrors mounted back-to-back on a sled, which moves on low friction magnetic bearings along the optical beam, thus lengthening one optical path while shortening the other (see also [22]). After the beam re-combiner one output is forwarded through a filter wheel to the long wavelength detector channel (LW, 110-210 μm). The second output is forwarded through a second filter wheel to a dichroic, which further splits the

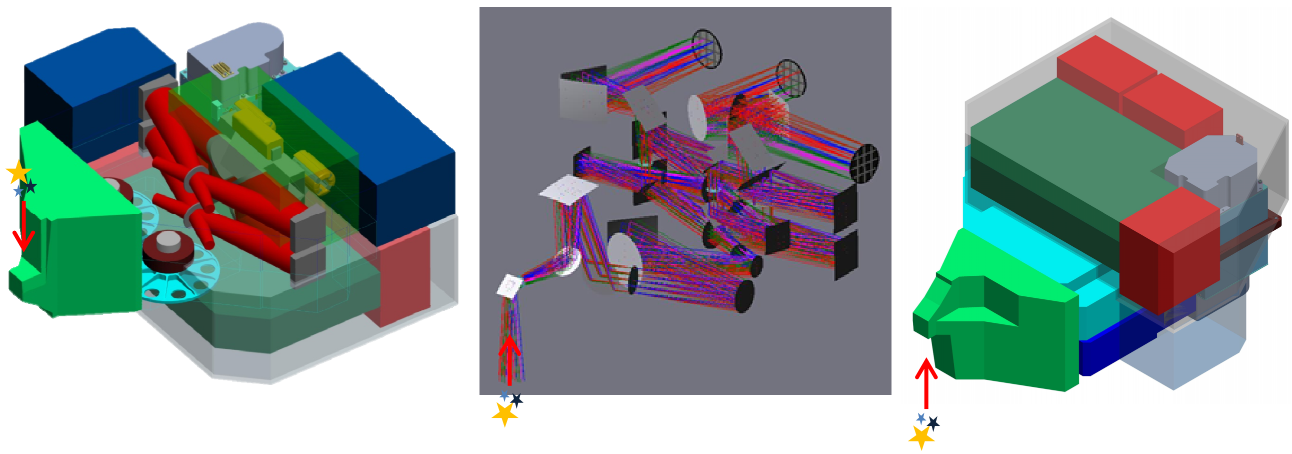

Figure 8 The SAFARI Focal Plane Unit (FPU) and its optics layout. The left panel shows the FPU (partially worked open) viewed from the top; the infrared radiation from the telescope enters at the far left from the top as indicated by the red arrow. The right picture shows the FPU from the bottom side. The light green box contains the input optics, the red boxes represent the Focal Plane Assemblies (FPAs), the blue boxes house the filters for the readout wiring, and the dark green box house the camera bay optics where the FTS output signal is conditioned for the three bands. In the open view also the two filter wheels, the optical beams through the FTS (in red), and the FTS mechanism are shown. The middle panel, with the same orientation as the left panel, shows the optical path through the FPU from the POM on the bottom left to the three sensor chips on the top right.

signal into the medium and short wave bands (MW 60-110 µm and SW 34-60 µm respectively). To obtain spectra in full resolution mode (corresponding to $\lambda/\Delta\lambda \sim 2000$ at 100 µm) the FTS will be scanned over its full stroke of about 35mm, an operation that will take about 2 minutes.

The filter wheels are utilised to insert, when needed, dedicated filters into the optical path. The needed filter complement is currently being established, possibilities include narrow band filters and neutral density filters. Of these especially neutral density filters fulfil a clear science need – the highly sensitive TES detectors easily saturate for strong sources (see below), making observations of a significant number of galactic sources possible only with such a filter in the beam.

To be able to evaluate the instrument output levels when no signal is provided, a shutter is mounted at the instrument entrance, immediately following the Pick-Off Mirror. For further intensity calibration a switchable cold calibration source is foreseen as part of the FPU. The radiation of this source is coupled into the instrument optical path through the second entrance of the input beam splitter. Thus the calibration source can be used to characterise and monitor all instrument elements from the initial beam splitter onwards.

The FPU housing is strapped to the spacecraft 4.5 K level to maintain the entire structure and components within it at that temperature. Additionally the FPU needs to provide the cooling for the 300 mK and 50 mK levels required for the sensors in the Focal Plane Assemblies. This is accomplished with a low weight, hybrid cooler composed of a small demagnetization refrigerator (ADR) pre cooled by a sorption cooler. When recycling the cooler the thermal energy is offloaded through straps to the spacecraft 4.5 K and 1.7 K levels. The reference design cooler is dimensioned to operate at an efficiency of about 75%, allowing about 36 hours of continuous observing after a ~12 hour recycle phase. Similar systems have been employed successfully for the PACS [7] and SPIRE [12] instruments on-board of the Herschel observatory [1], more details on the SAFARI cooler can be found in [23] and [24].

3.2 Detectors and Focal Plane Assemblies

The SAFARI detector subsystem (for a detailed description see [25]) is one of the crucial elements governing the overall instrument sensitivity. For detection of the weak (Far) IR radiation Transition Edge Sensors (TES) are employed. In these devices a sensor is coupled to a large absorber which is weakly coupled to a cold bath. The sensor is biased to its transition state such that as IR energy is deposited into the absorber a change the device resistance occurs, leading to a current change through a series coil which is subsequently read out using a SQUID amplifier. Within the SAFARI consortium work is on-going to manufacture TES devices which have an optimal balance between noise performance and saturation characteristics. In Figure 9 examples are shown of TES sensor geometries currently under study for the SAFARI instrument together with a prototype design for a feed-horn assembly. The various aspects of TES and feed-horn development for the SAFARI instrument are described extensively elsewhere (e.g. [26], [27], [28] and [29]).

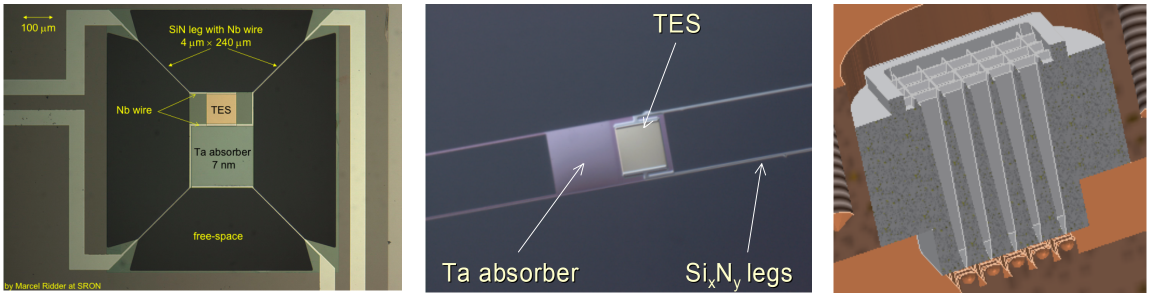

Figure 9 The SAFARI detectors and their feed-horns. The left two panels show examples of Transition Edge Sensor device geometries currently under study for the SAFARI instrument. The right panel shows a design for a prototype feed-horn assembly, focussing the incoming radiation on the TES absorber.

As the TES devices operate at very low temperatures –the current SAFARI design employs detector chips at a temperature of 50 mK– a dedicated structure needs to provide the proper level of thermal insulation from the 4.5K FPU structure. The Focal Plane Arrays (FPAs, see Figure 10) provide the mechanical support and thermal insulating structure, combined with the electromagnetic shielding required to shield the sensitive detectors against EMI from the satellite environment. The thermal insulation is achieved by firstly strapping the FPA housing to the 1.7 K satellite level and subsequently suspending the 50 mK detector mounting structure from a 300 mK intermediate temperature structure which is mounted to the inside of the FPA. To obtain the proper combination of stiffness and thermal insulation can Kevlar-based suspension structures are used. The design is extra challenging as on the one hand a high degree of thermal insulation needs to be guaranteed, while on the other hand the system has to endure the mechanical loads associated with the satellite launch.

Carrying the signals from all 4000 pixels separately to the Detector Control Unit (DCU) would give a prohibitively large number of wires in the instrument harness, and therefore a multiplexed readout scheme is required. For this purpose in the SAFARI instrument a Frequency Domain Multiplexing scheme will be implemented ([30], [31]). Each TES is equipped with an LC filter circuit tuned to a specific bias frequency and the TES signals are multiplexed by applying a comb of biases at different frequencies to a group of sensors. The outputs of these sensors is combined and fed to a single SQUID read out amplifier. The output of this amplifier, is then further amplified and forwarded to the DCU where it is de-multiplexed, allowing the original individual detector signals to be reconstructed for transfer to the ICU and subsequent transmission to ground. For SAFARI this multiplexing scheme will be used to combine groups of 160

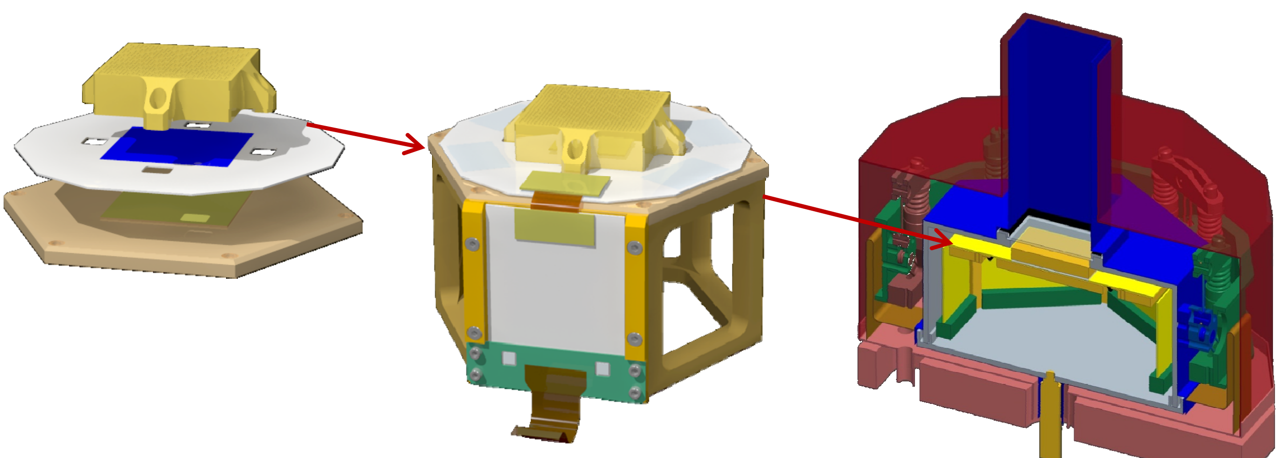

Figure 10 The SAFARI Focal Plane Assembly (FPA). The right two panels show the 50mK detector frame containing the sensor chip (the blue square) with the copper feedhorn block mounted on top. The detector base plate is mounted on a hexagonal frame, with the LC filter circuits used for the Frequency Domain Multiplexing and SQUID amplifiers mounted on side panels. The left panel shows the complete FPA with (in blue) the 50 mK Niobium and (in red) the 1.7K (Cryoperm) magnetic shields. Between these two the 300 mK intermediate temperature suspension level is seen (in green).

detectors, decreasing the number of wires in the harness by more than two orders of magnitude.

3.3 The warm electronics

The ICU is the single interface between SAFARI and the SPICA satellite for command, control and data. The ICU controls all instrument operations by means of is central control Data Processing Unit (DPU) aided by dedicated control and monitoring units for the various SAFARI elements; the cooler and general thermal control, the calibration source, the shutter, the FTS and the filter wheels. The DPU receives commands from the satellite, these commands will be verified by the On Board Software (OBSW) as being applicable/allowable under the current instrument condition, and if so they will be executed by sending instructions to the various instrument controllers including the Detector Control Unit. Each of the controllers will operate the relevant unit and regularly feed housekeeping information to the DPU. These data will be inspected to determine whether the instrument is operating properly and, if warranted, acted upon by adapting the instrument operation. In parallel all housekeeping information will be packaged and sent to the satellite for downlinking. One function of the OBSW will be to compress the science data received from the DPU to reduce the data volume before these are packaged in science telemetry packets and forwarded to the satellite for downlink to the ground. As all science data can be immediately forwarded to the satellite mass memory, the instrument itself has no need for any significant data storage capability. Additionally the ICU houses the primary instrument Power Supply Unit (PSU) responsible for supplying power to all SAFARI components except for the DCU.

The Detector Control Unit (DCU) houses all functionality to generate the biases for the detector system in the FPA's, condition and digitise the multiplexed detector signals, de-multiplex these and transmit these to the ICU. In the de-multiplexing also the base band feedback signal to optimally drive the front end chain is generated. The modulation feedback and the AC biases are generated in the digital signal processing stage of the DCU and subsequently converted to analogue signals and amplified for transfer back to the FPA's.

3.4 Instrument performance

Given the science goals of the SPICA project as a whole and the SAFARI instrument in particular obtaining the required sensitivity is essential – the satellite and the instrument promise astronomers to be background limited, i.e. limited only by the zodiacal emission and the cosmic background radiation.

To predict the performance of the SAFARI instrument, and whether it can make true on this promise, the elements determining the overall instrument throughput have been analyzed with respect to their impact. The sources that most directly influence the SAFARI noise budget are associated with the telescope and instrument optical paths, and the detector system, as indicated schematically in Figure 11. Firstly there is of course the dark noise (NEP - Noise Equivalent Power) of the detectors themselves, but added to that are the photon noise due to optical loading by background signals like sky background, telescope and baffle emission, emission from within the instrument itself, and any source of stray light. The magnitude for most of these can be estimated, albeit that to date no estimates exist for the level of stray light 'seen' by the SAFARI detectors. To estimate the on-sky sensitivity the NEP needs to be combined with the optical efficiency of the system, which is a combination of the FTS efficiency, the detector optical efficiency, and losses incurred due to the various filters needed to reject out-of-band emission. The resulting expected sensitivities are listed for the three SAFARI bands in Table 2 together with estimates for the important noise sources. It is clear that with the aimed for detector NEP of $\sim 2\times 10^{-19}$ W/√Hz the system performance

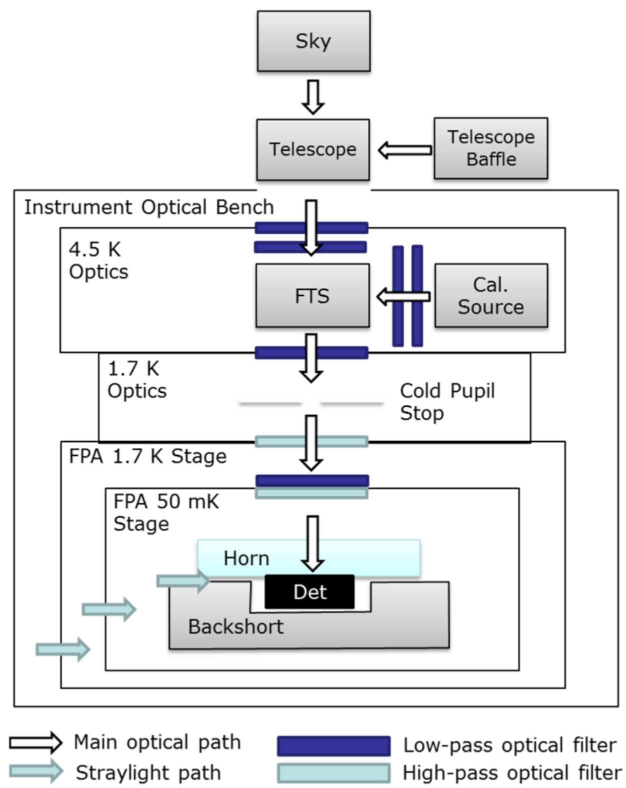

Figure 11 Components in the SAFARI optical path contributing to the overall system noise budget.

becomes determined largely by the background loading of the detectors. Assuming zero stray light, for the longer wavelengths and the nominal SPICA configuration that background loading is almost equally divided over the sky and ‘satellite’ background.

Table 2 Major noise contributors determining the SAFARI instrument performance. For the satellite nominal values are assumed; telescope temperature 6K, baffle temperature 14.5K, baffle coupling factor 10^{-4}. The impact of stray light is not included, and would further degrade the noise performance.

Source	LW	MW	SW
Total optical loading in aW	68	34	74
Photon NEP, in 10^{-19} W/√Hz			
- Sky background – extragalactic and zodiacal emission	3.2	4.2	8.4
- Telescope + baffle + instrument	2.6	0.4	
- Total	4.1	4.2	8.4
Detector dark NEP, in 10^{-19} W/√Hz	2.0	2.0	2.8
Total NEP, in 10^{-19} W/√Hz (At the detector, referenced to absorbed optical power)	4.6	4.7	8.8
Spectroscopic sensitivity on the sky, in 10^{-19} W/m^2 (5-σ, 1-hour)			
- single-pixel	2.9	3.0	3.3
- w. coadding	2.5	2.6	4.1
Photometric sensitivity on the sky, in µJy (5-σ, 1-hour)			
- single-pixel	32	19	12
- w. coadding	28	16	15

3.5 SAFARI operations

Although the operational scenario for the SPICA mission is not fully designed yet, a number of elements of SAFARI operations can be described already. Mostly these are purely instrument driven, although they do assume a Herschel-like operational scenario, as appropriate for an observatory operating at the L2 Lagrange point – long duration autonomous satellite observation with interspersed short duration periods in which (science) data are downlinked from the satellite to ground, generally with a 24/48 hour cycle.

Before observations with SAFARI can start a cooler recycle period is needed. The significant thermal load of the cooler recycling process will be prohibitive to any instrument operations, except possibly for the SPICA Focal Plane Camera (FPC) parallel mode. On the other hand satellite operations like data uplink and downlink, but also platform and orbit maintenance etc, likely are not impacted. Once the cooler is ready for operations a (short – TBC duration) period will be needed to allow thermal stabilization of the detectors in the FPAs. Subsequently the instrument will be configured for a series of standard calibrations to be carried out at the beginning of each observational period, firstly to verify proper operation of the system but also aimed at characterizing the long term behavior of the instrument and its subsystems. Following this a series of science observations will be executed, as planned by the SPICA science operations center, possibly with one or more dedicated (short) blocks of characterization measurement interspersed. This will continue until a predetermined moment, close to the end of the cooler hold time, when an operational period epilogue block will follow to obtain a last set of characterization parameters and to prepare the instrument for its standby mode. During the entire period the data from the instrument will be sent to the satellite for storage in the on board mass memory. Following the end of SAFARI operations the satellite high bandwidth X-band transmitter (nomally switched off during SAFARI operations to reduce the level of EMI) will be switched on to downlink the data to ground for further processing and forwarding to the astronomical community.

The instrument calibration and characterization data, as well as suitable science data, will be analyzed by the SAFARI Instrument Control Center (ICC), and used for further characterization of the instrument, refinement of its calibration and data processing facilities, and further optimization of its operations. Included in this is the responsibility of the ICC to maintain and where relevant further develop the SAFARI algorithms implemented in standard data processing pipeline, which is used in the SPICA (European) data center to provide standard data products for the astronomical community. In the development phase the ICC will prepare for this by developing the infrastructure –organization, procedures, software, hardware and facilities– necessary to support these activities. As the ICC operational environment is embedded in the overall SPICA operations, in the development phase the development of procedures and software will be done in close cooperation with ESA and the SPICA project.

SAFARI will have several main observing modes combining different aspects of the instrument capabilities. Each of the modes will include short (internal) calibrations (e.g. in spectroscopy mode a short scan on the internal calibrator) to ensure that the data for a given observation contain all the information needed to obtain a calibrated data set. Both in photometry mode and in any of the spectroscopy modes the instrument will have observing modes optimized for single point sources; a staring mode and/or a 3 or 5 point map to fully sample the telescope beam. Additionally mapping modes to efficiently cover (large) on sky areas will be implemented. For spectroscopic observations the mapping modes will follow a raster executing an FTS scan at each position. A fully sampled low noise image will be built up by combining (partly) overlapping fields of view with instrument pointing positions appropriately chosen such that fully Nyquist sampled images can be generated. Finally an on-the-fly photometry mode will be implemented in which data are taken continuously, with the FTS fixed in the ‘photometry position’, while the satellite scans across the sky area of interest.

3.6 Development challenges

Given the ambitious goals of both the SPICA mission as well as the SAFARI instrument naturally a number of technical challenges need to be overcome. The first challenge is to achieve the required sensitivity for the TES sensors. The project is well underway in this aspect, NEP’s within a factor of two of what is required has already been demonstrated in the lab, for individual sensors but also for small TES arrays. The next steps are to both improve this sensitivity and to demonstrate this for the larger size flight instrument arrays. A second prime issue is dealing with the various sources of electromagnetic interference which, due to the low output signal levels from the TES sensors and the extreme harness length, can easily lead to pick-up of unwanted signals. As a consequence high demands are put on the level of FPA and wire shielding and filtering. At the same time the SPICA platform, being cooled using mechanical coolers, is on a tight thermal budget, and thus both active and parasitic heat load need to be minimized. Clearly the harness itself can present a considerable parasitic heat load, and thus considerable attention needs to be spent on optimizing the harness shielding under the thermal constraints, while on the other hand more than in most missions all possible measures need to be put in place to reduce EMI levels and where possible eliminate EMI sources (e.g. by switching off the high bandwidth downlink transmitter) on the platform. A similar challenge arises from the interplay between the thermal environment requirements and the predicted satellite launch loads; as structures need to be made stiffer for larger launch loads, their parasitic thermal losses increase. For SAFARI this is found to be of relevance especially for the Kevlar strings which are used to provide the thermal insulation in the mounting brackets connecting the 50mK and 300mK levels to the insides of the FPAs – improvements in this area require a solid understanding of the true launch loads and options on how to reduce their effect on the instrument.

4. THE SAFARI PROJECT; STATUS AND OUTLOOK

4.1 The SAFARI consortium

A consortium has been established to develop and implement the SAFARI instrument as a European contribution to the SPICA mission. The European Space Agency ESA is the formal point of contact with the Japanese space agency JAXA and the SPICA project, and if the project is approved will be the party that formally hands over the SAFARI flight instrument to SPICA. As a consequence of that role, in the development phase ESA manages the SAFARI instrument interfaces.

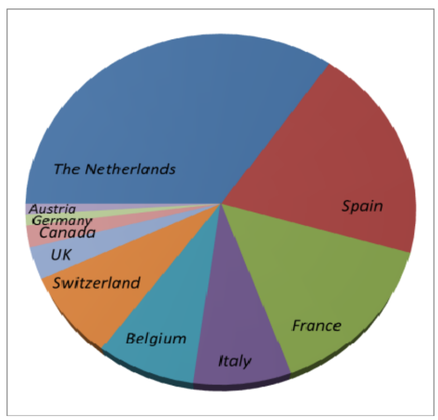

Figure 12 Indication of the level of involvement of the SAFARI consortium partners in the project

The SAFARI consortium is at this time quite well established, with as main large contributors the Netherlands, Spain and France and smaller contributions from various partners in Europe, Canada, and Japan. Figure 12 gives an indication of the relative level of involvement of the countries that are currently committed to support the SAFARI project, in Table 3 the current division of tasks over the partners is listed. As development continues and more knowledge is gained as to which technologies best suit the various elements of the system, the division of labor over the consortium is further optimized to maximally profit from the available consortium experience within the constraints of achievable national support.

In parallel with the development of the instrument the SAFARI science consortium is being established. A number of Science Co-Investigators will be identified who, jointly with the SAFARI project scientist, and under responsibility of the SAFARI principal investigator, are to lead the SAFARI science consortium and its science programme. The science consortium will jointly define what the priorities are of the various science areas that can be tackled with the instrument, and subsequently devise how the SAFARI guaranteed time can best be used to serve these priorities. An observing program will be designed and proposed with guidelines as to which consortium partners will tackle each part of the data reduction and science harvesting.

Table 3 distribution of tasks in the SAFARI consortium

Country	Institute(s)	Prime SAFARI hardware contribution
Netherlands	SRON	Principal Investigator, Project Manager, Project Scientist, instrument system engineering, system AIV, detector system
	TNO	FTS system
Spain	CAB/INTA	Focal plane structure and optics, filter wheels, mechanical lead
France	IRAP Toulouse	Detector control unit
	CEA Grenoble and Saclay	Sub kelvin cooler system including control electronics, thermal lead
Italy	IFSI/INAF	Instrument control unit, OBSW, warm interconnect harness
	INAF/Thales	Low noise amplifiers
Belgium	KU Leuven/CSL	Environmental qualification, AIV support, magnetic bearings, calibration lead
Switzerland	ETH	Calibration source (TBC), shutter
	Univ. of Genève	ICC lead
United Kingdom	Univ. of Cardiff	Filters, beam splitters and dichroics
	Univ. of Cardiff, Univ. of Cambridge, RAL, UCL	Detector components, filters and quasi-optics, system design and analysis support
Germany	PTB, MPE	TES SQUID amplifiers, test support
Canada	University of Lethbridge	FTS modelling, FTS testing, TDM and FDM data readout support
Austria	Univ. of Vienna	OBSW compression/decompression software
Ireland	NUI, Maynooth	Detector EM/optical modelling
Japan, Univ. of Tokyo; Denmark, DTU; Sweden, Univ. of Stockholm – hardware contribution TBD		

4.2 Project outlook

The last years have seen a number of significant achievements. A first major step was the selection of the TES based system out of four different detector options in June 2010. From that moment onwards the limited resources of the consortium could be concentrated fully on a single detector technology. The detector development has since been successful in demonstrating detector noise levels already close to what is needed to fulfill the instrument sensitivity requirements. In parallel, development of the frequency multiplexed readout scheme has been demonstrated to work for 54 pixels. A detector concept review held early 2012 clearly identified the progress, although, not unexpectedly, the review also underlined that even with these successes completing the full system within the current SPICA timeline would still be a significant challenge. In other areas great progress has been made as well; as an example the sub-kelvin cooler concept has been fully validated, and manufacture of the demonstration model is expected to commence shortly.

At this time the SAFARI project is preparing for the definitive approval of the SPICA mission, expected in the course of 2013. In this preparatory phase a number of exploratory studies are carried out to obtain the optimal instrument design compatible with the project constraints. Where needed activities are undertaken to support the SPICA project in its preparations towards the project go-ahead, explicitly for the currently on-going SPICA risk mitigation phase. The current SAFARI planning is aimed at delivery of the flight instrument by late 2019, with a project preliminary design review already at the beginning at 2015, and concept design reviews leading up to that.

5. SUMMARY

The SPICA far-infrared Space Observatory, to be launched in the early 2020s, will provide astronomers with the most sensitive view ever of the cold and obscured universe. This leap in sensitivity is made possible because SPICA is the first space observatory to have a large mirror which is cooled to temperatures close to absolute zero. Only with such a cold telescope can astronomy fully profit from the world's most sensitive sensors at far-infrared wavelengths, such as developed for the SAFARI far-infrared imaging spectrometer. SPICA will take its place among the great new space and ground based facilities such as JWST, IXO, ALMA, SKA and ELT, offering unique, new and crucial diagnostics of the universe. With the low background level of SPICA SAFARI will, for the first time, provide astronomers the means to observe infrared sources as weak as the background noise from the universe itself. SPICA will allow astronomers to address a huge variety of areas of interest, from planet formation and solar system structure to galaxy evolution and cosmology.

REFERENCES

[1] M. Clampin, "Overview of the James Webb Space Telescope observatory", in *Proc. SPIE Vol. 8146, UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts V*, Howard A. MacEwen; James B. Breckinridge, Editors, pp. 814605-814605-10 (2011)

[2] G. L. Pilbratt, *et al.*, "Herschel Space Observatory An ESA facility for far-infrared and submillimetre astronomy," *Astronomy & Astrophysics*, vols. 518 and 521 (2010).

[3] B. Swinyard, T. Nakagawa, *et al.*, "The space infrared telescope for cosmology and astrophics: SPICA A joint mission between JAXA and ESA," *Experimental Astronomy*, vol. 23, pp. 193-219 (2009).

[4] A. Poglitsch, *et al.*, "The Photodetector Array Camera and Spectrometer (PACS) on the Herschel Space Observatory," *Astronomy & Astrophysics*, vol. 518, L2 (2010).

[5] The Hubble telescope, http://www.nasa.gov/hubble, http://www.stsci.edu/hst/

[6] A.C, Fabian, "The obscured growth of massive black holes" MNRAS, 309, L39 (1999)

[7] D. Richstone, E.A. Ajhar, R. Bender, G. Bower, A. Dressler, S.M. Faber, A.V. Filippenko, K. Gebhardt, R. Green, H.L. Ho, J. Kormendy, T.R. Lauer, J. Magorrian, S.A. Tremaine, "Supermassive black holes and the evolution of galaxies", Nature, 395, A14+ (1988)

[8] J. Magorrian, S. Tremaine, D. Richstone, R. Bender, G. Bower, A. Dressler, S.M. Faber, K. Gebhardt, R. Green, C, Grillmair, J. Kormendy, T. Lauer, "The Demography of Massive Dark Objects in Galaxy Centers", AJ, 115, p. 2285 (1998)

[9] L. Ferrarese, D. Merritt, "A Fundamental Relation between Supermassive Black Holes and Their Host Galaxies", ApJ, 539, L9 (2000)

[10] L. Ferrarese, H. Ford," Supermassive Black Holes in Galactic Nuclei: Past, Present and Future Research", Sp. Scie. Rev., 116, p. 523 (2005)

[11] F. Shankar, D.H. Weinberg, J. Miralda-Escudé, "Self-Consistent Models of the AGN and Black Hole Populations: Duty Cycles, Accretion Rates, and the Mean Radiative Efficiency", ApJ, 690, p. 20 (2009)

[12] L. Spinoglio, K. M. Dasyra, A. Franceschini, C. Gruppioni, E. Valiante, K. Isaak, "Far-IR/Submillimeter spectroscopic cosmological surveys: predictions of infrared line luminosity functions for z<4 galaxies", *Astrophys. J.*, 745, 171, 2012

[13] NASA Exoplanet Archive, http://exoplanetarchive.ipac.caltech.edu/index.html

[14] M. W. Werner, *et al.*, "The Spitzer Space Telescope Mission," *The Astrophysical Journal Supplement Series*, 154:1–9, Sept., 2004.

[15] K.H. Ki, D,M, Watson, P. Manoj, E. Furlan, J. Najita, W.J. Forrest, B. Sargent, C. Espaillat, N. Calvet, K.L. Luhman, M.K. McClure, J.D. Green, S.T. Harrold, "Mid-Infrared Spectra of Transitional Disks in the Chamaeleon I Cloud", ApJ, 700, p.1017 (2009)

[16] B.A. Sargent, W.J. Forrest, C. Tayrien, M.K. McClure, D.M. Watson, G.C. Sloan, A. Li, P. Manoj, C.J. Bohac, E. Furlan, K.H. Kim, J.D. Green, "Dust Processing and Grain Growth in Protoplanetary Disks in the Taurus-Auriga Star-Forming Region",ApJS, 182, p.477 (2009)

[17] N. Evans, M.M. Dunham, J.K. Jorgensen, M.L. Enoch, B. Merín, E.F. van Dishoeck, J.M. Alcalá, P.C. Myers, K.R. Stapelfeldt, T.L. Huard, L.E. Allen, P.M. Harvey, T. van Kempen, G.A. Blake, D.W. Koerner, L.G. Mundy, D.L.

Padgett, A.I. Sargent, “The Spitzer c2d Legacy Results: Star-Formation Rates and Efficiencies; Evolution and Lifetimes”, ApJS, 181, p321 (2009)
[18] M.R. Meyer, J.M. Carpenter, E.E. Mamajek, L.A. Hillenbrand, D. Hollenbach, A. Moro-Martin, J.S. Kim, M.D. Silverstone, J. Najita, D,C, Hines, I. Pascucci, J.R. Stauffer, J. Bouwman, D.E. Backman, D. E. , “Evolution of Mid-Infrared Excess around Sun-like Stars: Constraints on Models of Terrestrial Planet Formation”, ApJ, 673, L181 (2008)
[19] B. Acke, M. Min, C. Dominik, B. Vandenbussche, B. Sibthorpe, C. Waelkens, G.Olofsson, P. Degroote, K. Smolders, E. Pantin, M.J. Barlow, J.A.D. Blommaert, A. Brandeker, W. De Meester, W.R.F. Dent, K. Exter, J. Di Francesco, M. Fridlund, W.K. Gear, A.M. Glauser, J.S. Greaves, P.M. Harvey, Th. Henning, M.R. Hogerheijde, W.S. Holland, R. Huygen, R.J. Ivison, C. Jean, R. Liseau, D.A. Naylor, G.L. Pilbratt, E.T. Polehampton, S. Regibo, P. Royer, A. Sicilia-Aguilar, B.M. Swinyard, B. M. “Herschel images of Fomalhaut - An extrasolar Kuiper belt at the height of its dynamical activity”, AA, 540, p. 125 (2012)
[20] M. J. Griffin, *et al.*, “The Herschel-SPIRE instrument and its in-flight performance,” *Astronomy & Astrophysics*, vol. 518, L3 (2010).
[21] B. M. Swinyard, *et al.*, “The FIRST-SPIRE spectrometer a novel imaging FTS for the sub-millimetre,” in *Proc. SPIE Vol. 4013*, Munich, 27-31 March (2000).
[22] T. C. van den Dool, *et al.*, “SPICA/SAFARI cryogenic magnetic bearing Fourier transform spectrometer mechanism,” in *Proc. Int. Conf. On Space Optics (ICSO 2010)*, Rhodes, Greece, 4-8 October, 2010.
[23] L. Duband, *et al.*, “SPICA/SAFARI subkelvin cryogenic chain,” Cryocoolers 16, in *Proc. 16th Int. Cryocooler Conference*, Atlanta USA, 18-20 May, 2010.
[24] L. Duband, JM Duval, N. Luchier and T. Prouve, *Cryogenics* 2012 vol. 52, p. 145-151
[25] B. D. Jackson, P. A. J. de Korte, J. van der Kuur, P. D. Mauskopf, J. Beyer, M. P. Bruijn, A. Cros, J. R. Gao, D. Griffin, R. den Hartog, M. Kiviranta, G. de Lange, B.-J. van Leeuwen, C. Macculi, L. Ravera, N. Trappe, H. van Weers, and S. Withington, “The SPICA-SAFARI Detector System: TES Detector Arrays with Frequency Division Multiplexed SQUID Readout”, IEEE Transactions on Terahertz Science and Technology, 2012, Vol 2, p. 12
[26] D.J.Goldie ,J.R.Gao, D.M.Glowacka, D.K.Griffin, R.Hijmering, P.Khosropanah, B.D.Jackson, P.D.Mauskopf, D.Morozov, J.A.Murphy, M.Ridder, N.Trappe, C.O’Sullivan, S.Withington, Ultra-low-noise Transition Edge Sensors for the SAFARI L-band on SPICA, SPIE 2012, Amsterdam (Conference 8452)
[27] Goldie, D.J.,Velichko, A.,Glowacka, D.M., Withington,S.,“Ultra-low-noise MoCu transitonedge sensors for space applications”, *J. Appl. Phys.* 109, 083105(2011).
[28] P. Khosropanah, R. Hijmering, M. Ridder, J.R. Gao, D. Morozov, P.D. Mauskopf, N. Trappe, C. O’Sullivan, A. Murphy, D. Griffin, D. Goldie, D. Glowacka, S. Withington, B.D. Jackson, D. Audley, G. de Lange, “Short-wavelength band TES Arrays for the SAFARI Instrument on SPICA”, SPIE 2012, Amsterdam (Conference 8452).
[29] P. Khosropanah, R.A. Hijmering, M. Ridder, M.A. Lindeman, L. Gottardi, M. Bruijn, J. van der Kuur, P.A.J. de Korte, J.R. Gao, H. Hoevers, A Distributed TES Model for Designing Low Noise Bolometers Approaching SAFARI Instrument Requirements, *Journal of low temperature physics*, 167, 188, (2012)
[30] J. van der Kuur, P.A.J. de Korte, H.F.C. Hoevers, M.P. Bruijn, M.L. Ridder, M. Kiviranta, H. Seppä, Frequency-domain multiplexing development for high-count-rate microcalorimeters, *Nuclear Instruments and Methods in Physics Research*, A 559, (2006) 820–822
[31] R. den Hartog, J. Beyer, D. Boersma, M.P. Bruijn, L. Gottardi, H.F.C. Hoevers, R. Hou, M. Kiviranta, P.A.J. de Korte, J. van der Kuur, B.J. van Leeuwen, M. Lindeman, A. Nieuwenhuizen, “Frequency Domain Multiplexed Readout of TES Detector Arrays With Baseband Feedback”, *IEEE Trans. Appl. Supercond.*, Vol. PP, Issue 99, pp. 1-5 (2011).