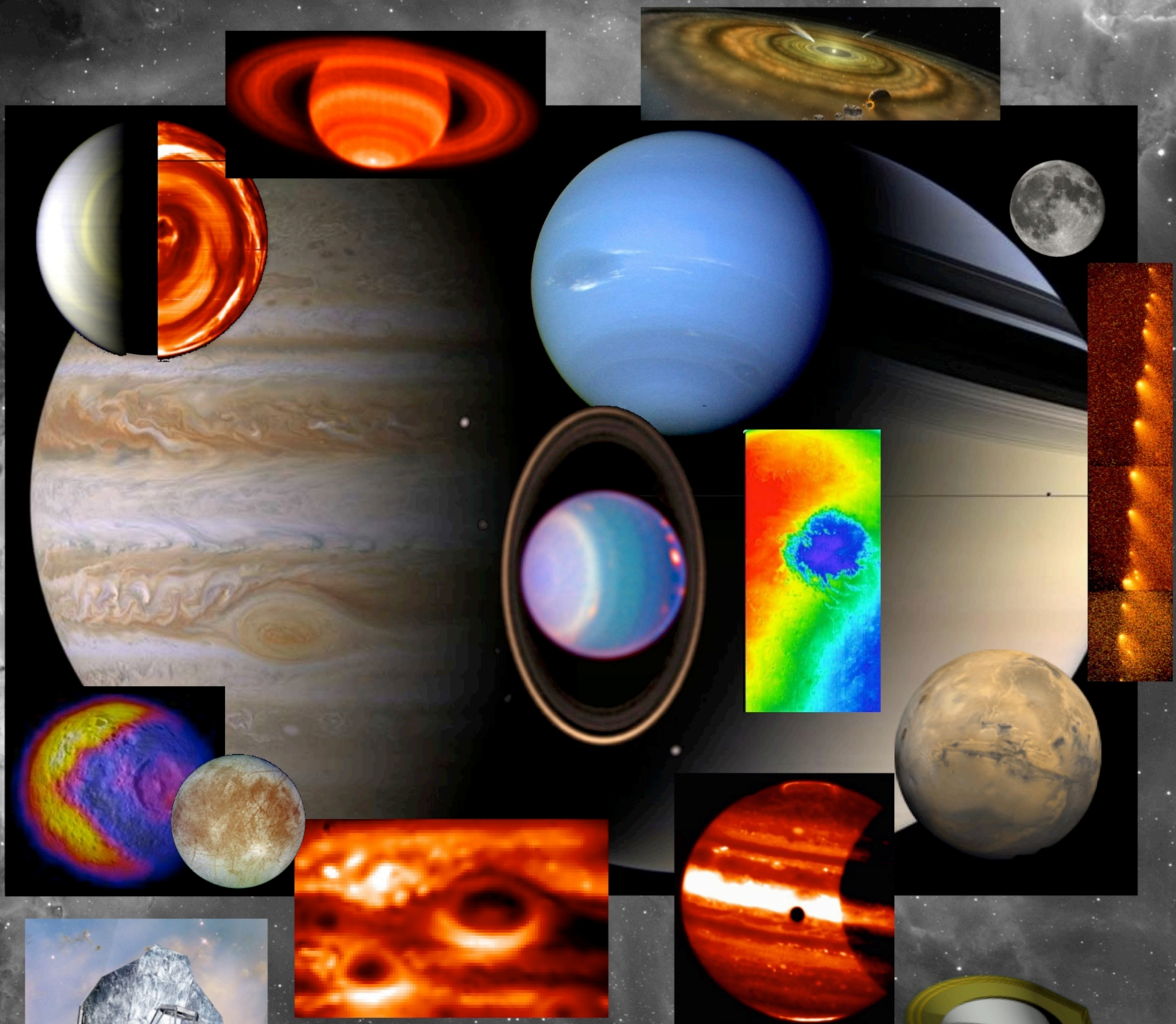
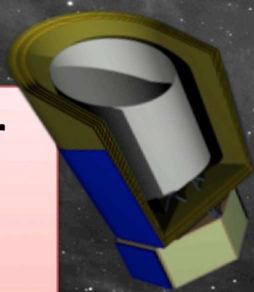
Exploring Planetary Origins and Environments in the Infrared

A PLANETARY SCIENCE INFRARED OBSERVATORY (PSIO)

A White Paper Response to ESA's Call for L-Class Science Themes





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Exploring Planetary Origins and Environments in the Infrared: A Planetary Science Infrared Observatory (PSIO)

WHITE PAPER RESPONSE TO ESA CALL FOR LARGE-CLASS SCIENCE THEMES

Executive Summary

The discovery of large numbers of extrasolar planets has shown that the formation of diverse planetary systems is a common phenomenon throughout our galaxy, and yet many of the fundamental questions about the origins, evolution and environmental conditions within our own solar system remain unanswered. We propose an ***observatory-class ESA mission to provide spatially resolved infrared spectroscopy of solar system and planetary objects in all their guises***, from their **origins** (remaining debris in our solar system and planet-forming discs around other stars) to their present-day appearance (**atmospheres**, **surfaces** and **interactions** with their host stars for planets in our solar system and beyond). Discovery level science will be achieved by: combining broadband spectral coverage from 3-1000 μm with high spatial resolutions from a single mirror or distributed array; long time-baseline observations for evolving planetary processes and time-domain solar system science; and selected high-spectral resolution observations to probe regimes never previously explored by observatories or visiting spacecraft. Although this white paper focuses on the infrared exploration of our Solar System to address themes at the heart of Europe's Cosmic Vision, such a facility would be of immense value to the broader astrophysical community. In particular the thermal-IR will allow probing of cooler transiting exoplanets existing within the habitable zone and low temperature brown dwarfs. The intention of this white paper is to ensure that ESA's future cornerstone missions, either as observatories or as visiting spacecraft, ***retain infrared solar system observations at the core of their scientific objectives***, and to advocate for investment in the critical European technologies for high spectral and spatial resolution infrared spectroscopy.

Requirements for Planetary Science in the Infrared

- Observatory-class facility offering broadband thermal infrared spectral coverage from 3-1000 μm to address planetary science questions throughout our Solar System.
- Imaging spectroscopy at moderate resolution ($R\sim10^3$) to map environmental characteristics on solar system targets and relate to visible-light images.
- High resolution spectroscopy in narrow selectable spectral ranges ($R>10^6$) to probe unexplored parameter regimes for surfaces and atmospheres.
- Optimised for long duration (5+ years) to allow near-continuous monitoring of individual targets with regular observing campaigns for time-domain planetary astronomy.
- 3-5m class monolithic mirror or distributed array architectures to provide spatial resolutions 0.25-5.0" across the mid/far-IR.

Box 1 Summary of the requirements for an L-class observatory dedicated the exploring planetary systems in all their guises.

1. Motivation and Background

Infrared spectroscopy of thermal emission is the primary tool for investigating the environmental characteristics of surfaces, dust and atmospheres on objects in our solar system and beyond, and yet numerous space missions have overlooked this spectral range over the past decades in favour of reflectance spectroscopy at shorter wavelengths. This must change for future ESA cornerstone missions, particularly with the relentless improvements in the capabilities of ground-based astronomers to provide Hubble-quality visible/near-infrared imaging of our planetary neighbours. A space-based observatory is essential for thermal infrared science, to remove the obscuring influence of terrestrial atmospheric contaminants (particularly water, CO_2, methane and

O_3), whereas short-wavelength science will be readily provided from the ground in the coming decades, limiting the necessity for missions to include reflected sunlight experiments. In this white paper we describe the scientific advances that could be provided by a dedicated thermal infrared observatory for planetary science, utilising thermal emission across a broad spectral range spanning the capabilities of ISO, JWST, Spitzer, Herschel and SPICA from a single, agile space telescope dedicated to planetary observations. This would provide ***observations of multiple objects throughout a planetary system, from the smallest building blocks to the largest planets***. Such a facility would be of high value for targets both within and outside of our solar system, studying planetary formation and planetary environments in all of their diverse guises.

Why the thermal infrared? The thermal infrared encompasses many molecular (absorption and emission) and solid-state (ice absorption, dust emission/absorption) features. The strength of a feature depends upon the molecular abundances and the temperature of the line-forming region, in addition to the presence of continuum absorbers such as aerosols or dust. Deriving physical properties from these observations is inherently degenerate (for example, measuring temperatures using assumptions about the abundances of CO_2 or CH_4), and we must therefore ***capture as broad a spectral range as possible*** to unambiguously separate the different contributions. In the gaseous phase, middle atmospheric emission (stratosphere/mesosphere) features appear as narrow Doppler-broadened lines requiring high spectral resolution to resolve their line-shape and determine temperatures and composition. Tropospheric lines, conversely, are pressure-broadened and require lower-resolution spectroscopy. Solid-state features such as astrophysical silicate absorption, or water ice bands on satellite surfaces, can have broad features that render them difficult to identify without broadband spectroscopy. An ***infrared observatory must therefore be adaptable, featuring both moderate resolution imaging spectroscopy ($R\sim10^3$) and the capability for high spectral resolutions ($R>10^6$)*** to sample as broad a range of line-forming environments as possible.

Why dedicated to planetary observations? Previous infrared remote sensing has either relied on filtered photometric imaging in a small number of discrete wavelengths within the infrared windows or point spectroscopy that needs to be scanned over targets to create an image. Planetary astronomy needs: a) ***long-term continuous observations of planetary phenomena, simultaneously across a broad wavelength range and capturing the spectra of all points on a planet simultaneously,*** with a similar spatial resolution; and b) the need for an ***agile, responsive platform able to move quickly to observe events of interest in our dynamic solar system***. Despite several decades of planetary astronomy, our knowledge of these environments comes from simple, isolated snapshots, whose frequency cannot be tuned to the timescales of interest (e.g., rapid-scale impacts or meteorological events to long-term seasonal evolution). Furthermore, comparative planetology is hampered when a single target is studied in detail at a mission rate of typically no more than once per decade with visiting spacecraft. A facility that could ***observe all targets with the same instrumental capabilities*** would satisfy a broader swathe of the community than a single targeted mission. Finally, the observational ***requirements of the deep sky astronomical community are rather different to those of planetary observers***, who desire: large fields of view (an arc minute for Venus and Jupiter); broadband spectroscopy of varying spectral resolution; enhanced spatial resolution and the ability to view the brightest targets; and the capability to observe a target for a long period of time, whilst responding quickly to unique events. No observatory presently planned can meet these observational requirements.

Building on our Infrared Heritage

Despite the great diagnostic value of the thermal infrared, this spectral range has been utilised on relatively few planetary missions. Venera 15/16 were the last to study Venus' thermal-infrared spectrum three decades ago; and only two capable long-wavelength spectrometers have been sent to study the outer solar system, namely IRIS on the twin Voyager spacecraft and CIRS on the Cassini mission. These delivered a huge change in our understanding of atmospheric climate, circulation and chemistry on the giant planets and the properties and endogenic activity on icy satellites and rings, but such studies are not destined to be repeated in the coming decades. Jupiter, for example, has never been observed by an orbital mission with good infrared capabilities: Galileo had a very simple thermal imager which was ultimately limited to only two spectral channels; Juno does not have capabilities longward of 5 µm; and JUICE will not feature any thermal infrared instrumentation. Without maps of the evolving temperatures, wind shears, humidity (e.g., ammonia) and clouds, our understanding of Jupiter's meteorology and climate will be woefully incomplete. We advocate that ***thermal infrared science should be a primary component of any future ESA cornerstone mission*** in our solar system, but that a space-borne planetary observatory would provide enhanced science to all missions planned or in flight.

Today, planetary astronomy is being driven both by space observatories and ground-based facilities, although atmospheric variability, particularly in the water vapour column, prevents accurate radiometric calibration, and regions contaminated by strong telluric features are largely unusable from the ground. The Stratospheric Observatory for Infrared Astronomy (**SOFIA**, 2.5-m mirror with a suite of instruments covering the 5-240 µm range) overcomes some of these obstacles by flying at high altitude, although its observing capabilities are limited by competition, flight paths and the stability of the residual atmosphere above the aircraft. ALMA will provide unprecedented results beyond 300 µm, but will still be limited by telluric contamination. ***Hence, access to the mid- to far-IR spectral ranges and well-calibrated data requires a space-borne platform***. ESA's Infrared Space Observatory (**ISO**, 2.3-240 µm with a 0.6-m primary mirror and a maximum R~30,000), **Spitzer** (0.85-m primary mirror, 3-180 µm and a maximum R~600), **AKARI** (0.67m primary mirror, 1.8-180 µm with R~135 at short wavelengths) and **Herschel** (3.5-m primary mirror, spanning 55-672 µm with heterodyne spectroscopy at the longest wavelengths) revolutionised our understanding of planetary conditions in our solar system, but were limited to disc-averaged snapshot observations of all targets. None of these observatories could provide heterodyne resolutions in the mid-infrared; none could provide imaging spectroscopy; none combined mid and far-IR in a single instrument chain; and none could provide the dedicated solar system observations required to address the science case below.

Enhancing our Infrared Future

In the coming decade, solar system science should form a substantial component of both the James Webb Space Telescope (**JWST**, with a 6.5-m primary mirror and a resolution up to R~3730 with the 5-28 µm MIRI instrument) and Space Infra-Red Telescope for Cosmology and Astrophysics (**SPICA**, 5-210 µm with a 3.2-m primary mirror). Although neither observatory is optimised for planetary studies (for example, the integral field units of JWST/MIRI's have a small FOV, ranging from 3.6" at 5 µm to 7.6" at 28 µm, and will require substantial mosaicking to image Jupiter), and neither will be able to provide long-term observations of a single target due to intense competition with deep sky phenomena, several solar system targets will be within their grasp. Mars and Venus will be beyond the reach of JWST beyond 5 µm, but several modes will be available for the giant planets (Jupiter can only be viewed at wavelengths shorter than 10 µm due to brightness limits), comets and cool rocky bodies (Lunine et al., 2010). SPICA is expected to survey a large number of Kuiper Belt Objects (KBOs) and Trans-Neptunian Objects (TNOs) in the far-IR, detect zodiacal dust clouds out to tens of parsecs, and study the roles of water and dust in planet-forming discs (Tamura et al., 2009, SPICA Workshop).

However, it is unlikely that either of these observatories could dedicate significant time to the solar system, and neither provide coverage of both the mid-IR and far-IR/sub-mm with the tunable spectral resolution from moderate (10^3) to heterodyne (10^7) as proposed here. To complement JWST and SPICA and provide a new compelling platform for the astrophysical community, this proposal seeks to add (i) long baseline observations with higher spectral resolutions in the mid-IR (3-30 µm); (ii) high spatial resolution (and wide FOV) from a distributed array and high spectral resolution in the far-IR (30-300 µm) and sub-mm (300-1000 µm); and (iii) the agility to respond quickly and track any new phenomena observed within our solar system.

2. Outline: A Infrared Observatory for Planetary Astronomy

The science case outlined below can be summarised as follows:

Understanding the processes responsible for shaping planetary systems and the diverse environments found throughout our solar system.

The science case is sub-divided into four themes – Origins, Atmospheres, Surfaces, and Interactions, and requires a program dedicated to planetary systems at all stages in their evolutionary history, from planet-forming discs, to remnant debris of the earliest accretion stages, to end products of the formation process manifested as the bewildering array of planetary objects we see today. The aim of this white paper is to make the case for long-term thermal infrared (3-1000 µm) observations of planetary environments, both within our solar system and around other stars. The basic architecture of an observatory should achieve all or a subset of the following goals:

- **Enhanced Spectral Range:** Access to the 3-1000 µm spectral range with broadband moderate resolution imaging spectroscopy ($R\sim10^3$) and tunable heterodyne narrowband spectroscopy in narrow ranges ($R>10^6$).
- **Time-Domain Science:** A flexible and agile platform able to respond quickly to new and interesting events, and to observe single targets with a time sampling tuned to the phenomenon of interest (e.g., tracking atmospheric features over hours, planetary impacts, volcanism/cryovolcanism, or seasonal evolution over years).
- **Superb Spatial Resolution:** Diffraction-limited system at 5 µm, providing spatial resolution in the mid-IR from a single mirror (3 to 5-m class) and in the far-IR/sub-mm from a distributed array.

Such an observatory would build on ESA's heritage from ISO and Herschel, complement flight missions that do not have capabilities beyond 5 µm, and move beyond the planetary science capabilities of JWST and SPICA. Unlike spacecraft dedicated to a single target, an observatory is capable of addressing compelling scientific questions for multiple planetary objects. And by moving beyond single snapshots, we will open up the field of time-domain planetary science, analogous to the enormous leap from still photography to moving pictures, and permit pioneering breakthroughs in the field analogous to today's monitoring of terrestrial atmospheric phenomena and solar variability.

Target	Diameter	Target	Diameter
Venus	66"	Neptune	2.4"
Mars	25.1"	KBO/Pluto	0.11"
Ceres	0.84"	Io	1.2"
Vesta	0.64"	Ganymede	1.8"
Jupiter	50.1"	Titan	0.8"
Saturn	20.1"	Triton	0.13"
Uranus	4.1"		

Table 2 Maximum angular size of various solar system targets as viewed from Earth, measured in arcsec. For most examples, this is the maximum angular size at opposition. This should be compared to Table 1 to assess the capabilities of resolving these targets at infrared wavelengths.

Infrared observing has been historically difficult, requiring cold telescopes, cold instruments and large apertures to enhance spatial resolution, and in section 4 we describe pathways to achieving these objectives. We envisage a 3.5-5.0 m primary for this observatory and for reference, Table 1 shows how the diffraction limited spatial resolution of a range of mirror sizes varies with wavelength. This can be compared to the observed angular sizes of a range of targets in Table 2.

Although this white paper focuses on advances in our understanding of the solar system, such an ***observatory must also be cross-disciplinary and highly beneficial for the study of extrasolar systems***, particularly for cooler planets orbiting within habitable zones, as their peak emission will occur at longer wavelengths than the hot Jupiters and Neptunes that are the primary target of currently-planned exoplanet characterisation

Telescope	ISO	EChO	Herschel	Palomar	JWST	Keck
Wavelength (µm)	**0.6**	**1.5**	**3.5**	**5**	**6.5**	**10**
5	2.1"	0.84"	0.36"	0.25"	0.19"	0.13"
10	4.2"	1.6"	0.72"	0.50"	0.39"	0.25"
25	10.5"	4.2"	1.8"	1.3"	0.97"	0.63"
100	41.9"	16.8"	7.2"	5.0"	3.9"	2.5"
1000	419.4"	167.8"	72.0"	50.3"	38.7"	25.2"

Table 1 Diffraction limit for a range of observatory primary diameters (in metres) in the 5-1000 µm range (numbers are in arcseconds, for comparison with object angular diameters). Note that any Earth-based observatory (such as Keck) would suffer from seeing fluctuations in the range of 0.4-1.0 arcsec. The angular resolution of the 3.5-5m class observatories should be compared to the targets listed in Table 2 to give an idea of the proposed capabilities of PSIO for each target.

missions. However, exoplanet science places enormous constraints on telescope stability and detector sensitivity, and these science targets are the subject of other white papers. Our purpose is not to define a single observatory that is capable of addressing each of these science goals equally, but rather to demonstrate the unique science that can be achieved in this spectral range, and why it should form a crucial part of any future observatory or spacecraft mission.

3. Science Themes: Understanding Planetary Systems

In the following sections, we identify the key science questions that spatially-resolved infrared spectroscopy seeks to address, related to ESA's cosmic vision objectives - *what are the conditions for planet formation and the emergence of life; and how does the solar system work?*

Theme I: Origins

Key Question: What processes govern planetary formation, the architecture of our planetary system and the evolution of habitable environments?

The present-day architecture of our solar system is the end product of a variety of processes that we are only beginning to understand. Theory suggests that early accretion of planetary building blocks, composed of varying amounts of rock and ice depending on the conditions within the early nebula, determined the chemical makeup of the planets that we see today (e.g., Mizuno 1980). Subsequent migration of the planets, especially Jupiter and Saturn, redistributed the giant planets and leftover debris (comets, asteroids, KBOs, TNOs and the Oort cloud) to their present locations, and created the stable, habitable conditions we observe in our inner solar system today. Confirmation of these theories requires observational evidence, both from our own solar system and in planetary nurseries around other stars. The proposed observatory would ***employ remote sensing of atomic, molecular, isotopic and solid state signatures to understand the evolution of our solar system*** (e.g., Figure 1).

Giants: The giant planets were the final repositories for nebula gases hydrogen and helium, in addition to icy planetesimals trapping volatile species. Their bulk composition bears witness to the ratios of elements and isotopes in the source reservoirs, and detailed comparisons between the four giants would reveal shared reservoirs and common formational processes (e.g., Atreya et al., 1999). Although some species are locked away in deep condensation clouds (e.g., O/H cannot be measured due to the condensation of deep H_2O clouds), and others have no spectral signatures (e.g., noble gases), high spectral-resolution remote sensing will provide comparisons of elemental enrichments of cosmologically abundant species (C, N, P, S) and isotopic ratios (D/H, $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{18}O/^{16}O$). C/H appears to increase with radial distance from the Sun, but the deuterium

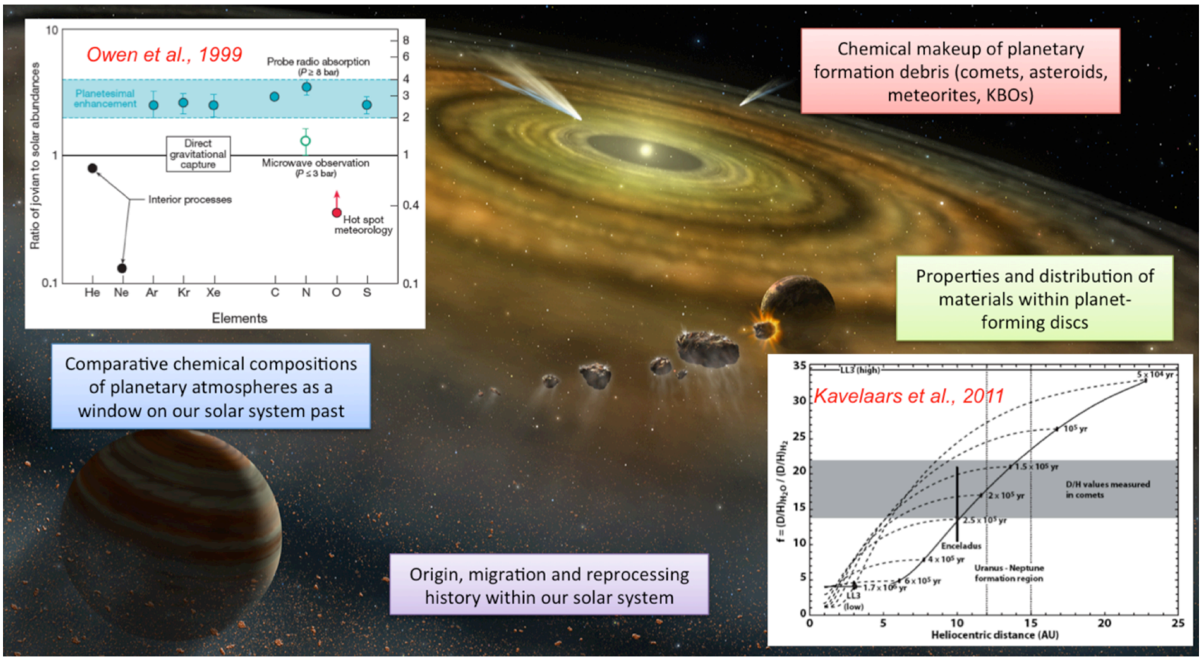


Figure 2 Thermal infrared spectroscopy from PSIO will be used to assess the elemental and isotopic inventories of a variety of solar system targets, from planetary atmospheres to icy and rocky material left over from the birth of our solar system.

enrichment groups the giants into two categories, the ice giants being enhanced in deuterium compared with the gas giants (e.g., Feuchtgruber et al., 2013 from Herschel and ISO studies). Far-IR sounding of the hydrogen-helium continuum will provide an accurate measure of the helium inventory on each planet (e.g., Conrath and Gautier, 2000), crucial to understanding the cooling history of the giants. Furthermore, far-IR sounding is sensitive to the peak of the Planck emission from the cool atmospheres of Uranus and Neptune, allowing a re-determination of their intrinsic heat flux for the first time since Voyager (e.g., Pearl et al., 1991). Furthermore, these same elemental enrichments, if detected on extrasolar giant planets, will allow us to identify common formation scenarios in different planetary systems (for example, the C/O ratio determined from transit spectroscopy could reveal their carbon-rich or oxygen-rich origins, (Madhusudhan 2012). By ***comparing the elemental and isotopic enrichments of multiple giant planet atmospheres,*** this observatory will place constraints on the chemical inventories of different planetary systems.

Debris: The composition of the giants will be ***compared with the chemical make-up of rock-ice remnants of planetary formation***, from comets and near-Earth objects, to asteroids, TNOs and KBOs. The volatile inventories of such objects, especially the fraction of water and deuterated species, will be used to understand the distribution of icy material in the early solar system. The D/H ratio in cometary H_2, H_2O and CH_4, from the Jupiter family, to long period and the newly-recognised families of main belt comets, will shed light on the delivery mechanism for volatiles to the early Earth, especially the origins of our world's oceans. For example, higher D/H ratios with radial distance from the Sun (e.g., Kavelaars et al., 2011, Figure 1) will support a cold, distant origin for Earth's water content. The properties of the surface ices, dust and minerals of planetary satellites, KBOs and TNOs will be revealed by a sensitive search for broadband spectral features, providing clues to ***their origins, subsequent migration and the nature of reprocessing over their history***. Finally, the sensitive constraints on the D/H ratio observed in terrestrial planet atmospheres (HDO on Venus and Mars) reveals insights into the loss processes for water from these worlds, and the potential limits of the habitable zone.

Discs: These compositional signatures provide a window onto the chemistry, radial mixing, disc-clearing and migrational processes at work in the early solar system, but to place these results in a broader context the infrared results must be compared with the spectral signatures of ices and dust in planet-forming nebulae, debris discs and protostellar discs. This would establish the validity of well-defined 'snow lines' and reveal the radial distributions of different source materials (carbon, deuterium, oxygen, nitrogen), while sampling the range of possible system architectures resulting from changes in stellar type and metallicity. The ***distribution of materials within our own solar system, revealed by infrared remote sensing, will be compared with planetary systems of various ages***, from the youngest planet-forming discs to the continuum of planetary types in established systems. Taken together, these observations will reveal the cycling of planetary building blocks within these systems.

Theme II: Atmospheres

Key Question: What powers the circulation, chemistry and dynamics of planetary atmospheres, from the deep troposphere to the thermosphere?

The combination of unprecedented infrared spatial resolution, tunable spectral resolutions and long-baseline observations will permit ***pioneering new studies of the atmospheres of Mars, Jupiter and Saturn, along with disc-averaged studies of rotational variability of the ice giants, Titan and planets around other stars*** (e.g., Figure 2). Solar system atmospheres are natural laboratories for testing our understanding of fluid processes and chemistry under extreme conditions, and provide a template for our understanding of planets around other stars. The infrared has long been the primary tool for studying the circulation, meteorology, chemistry and cloud formation in planetary atmospheres, using well-mixed species (H_2, CO_2, CH_4) as thermometers to map thermal structures in three dimensions and the plethora of emission and absorption features of minor species to trace the motion to understand compositional variability (e.g., Hanel et al., 2003). For those planets that can be spatially resolved, this observatory will address a long-standing problem by allowing us to match changes in albedo, winds and colouration observed in reflected sunlight (to be provided by simultaneous ground-based observations) to environmental parameters such as temperature, wind shear, gaseous composition (i.e., humidity) and cloud properties (e.g., Fletcher et al., 2010). By providing broadband spectroscopy with spatial resolutions approaching that of reflected-sunlight images, we will measure for the first time how these meteorological variations relate to the atmospheric plumes, waves, vortices, instabilities and the general banded structures that are commonplace in planetary atmospheres. This comprehensive meteorological study will not be achieved by future outer planet missions (NASA/Juno and ESA/JUICE for Jupiter) because of an absence of infrared spectral coverage. The observatory will ***reveal how energy, momentum and material are transported both horizontally and vertically from the troposphere to the thermosphere, allowing us to place the Earth's habitable atmosphere into its broader astrophysical context.***

Composition: High spectral resolutions in the mid and far-IR are a unique element of this proposal, allowing us to resolve narrow Doppler-broadened emission features in ***planetary stratospheres and mesospheres to probe atmospheric regimes typically ignored*** by studies sensitive only to tropospheres. UV photolysis, a close connection with planetary aurora, and an external influx of particles from comets, asteroids and dust produces a 'zoo' of chemical species in planetary upper atmospheres, which are then redistributed by the general circulation (for example, HCN in the atmospheres of Titan and Jupiter trace the atmospheric flow). High spectral resolutions will allow us to trace those species, determine their vertical profiles and to discover new ones to ***plug the gaps in our knowledge of atmospheric chemistry.*** Venus' stratospheric composition may be influenced by injections of sulphur-bearing materials due to geologic processes on the surface (e.g., volcanism), and these species could be mapped (by an IR observatory capable of viewing the inner solar system) to relate them to the UV-absorbent dark patches observed above the Venusian H_2SO_4 clouds, building on the near-IR discoveries of Venus Express. Mars' atmospheric water cycle and spatial distribution (e.g., the relation to topography and dynamics, Fouchet et al., 2007), the distribution of CO, temperature and winds will be monitored over seasonal timescales. Furthermore, Mars' atmospheric composition may be perturbed by episodic injections of methane (Formisano et al 2004; Mumma et al 2009), either from geologic or possibly astrobiological sources, and mapping the sources and sinks of Martian methane in the mid-IR is a crucial goal for understanding the atmospheric cycles on our closest neighbour. Trace species such as phosphine, arsine and germane, along with the far-IR signatures of the spin state of H_2 (ortho/para ratio, Conrath et al., 1998), will be used to understand disequilibrium processes and vertical

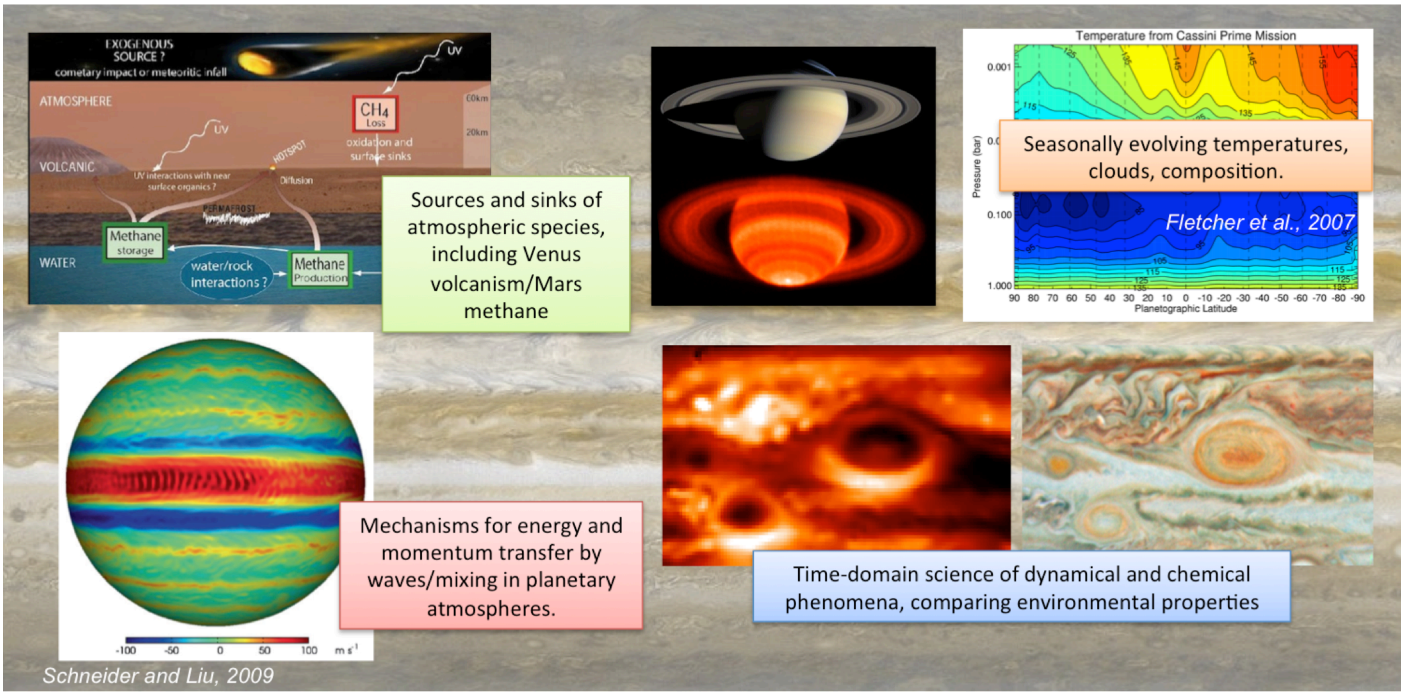


Figure 3 Imaging spectroscopy across the thermal infrared reveals the environmental variability associated with visible changes (atmospheric plumes, planetary impacts, volcanism, winds and waves, slow seasonal evolution), and near-continuous monitoring of rapidly-evolving targets will open up the field of time-domain planetary astronomy.

mixing within giant planet tropospheres. Finally, the chemistry of the thick N_2 atmosphere of Titan could well be representative of the type of environments observed on the pre-biotic Earth, and the cycle of methane between geological sources, seasonal lakes, seas, atmosphere and clouds will provide insights into this unique atmosphere long after the end of the Cassini mission. Regular disc-averaged observations of Titan at heterodyne resolutions in the mid-IR will be used to search for new species, determine vertical distributions and track compositional variability associated with methane-cloud activity to better understand the meteorological variability of this unique world.

Middle Atmosphere: Where heterodyne-resolution spectroscopy with $R \sim 10^7$ really provides advances is in measuring the Doppler shift and profiles of stratospheric lines, allowing us ***to map the three-dimensional wind structure above the cloud tops of Venus, Mars, Jupiter and Saturn for the first time***. Recent research has begun to reveal the dynamic nature of these stratospheres, with a multitude of wave phenomena (e.g., tropical oscillations similar to Earth's quasi-biennial oscillation, and horizontal thermal waves forced by tropospheric storms) and polar vortex phenomena (e.g., seasonally-variable polar collars on Saturn, Titan, Uranus and Neptune) with direct relevance to our own planet. Well-separated lines of CH_4, CO, and H_2O permit wind measurements in regions where there are no visible cloud tracers (e.g., Lellouch et al., 1991; Lellouch et al., 2008). By providing heterodyne resolutions in the mid-IR, we are able to provide wind speed measurements at spatial resolutions far exceeding the capabilities of Herschel. For example, Kostiuk et al. (2005) utilized ethane emission at 12 μm to measure Titan's middle atmospheric winds from the Subaru observatory with a 0.4" field of view. The vertical variability of zonal and meridional winds, particularly in association with vertically propagating waves, has far reaching implications for ***how planetary atmospheres move energy, momentum and material from place to place***. Furthermore, by opening up this 'middle atmosphere' on all of these planets, we will reveal the connectivity between the convective weather layers and the upper atmosphere, ionosphere and thermosphere. Indeed, energy transport by waves from below *could* be important in heating of the high atmospheres of the giant planets to temperatures far exceeding that expected from solar heating alone (e.g., Yelle et al., 2004), a situation termed the 'energy crisis.' However, the heating and cooling effects of gravity waves in particular have been demonstrated to be insufficient, (Hickey et al., 2000), so that ionospheric drag processes and Joule heating are sometimes invoked to explain the discrepancy (Muller-Wodarg et al., 2006). By mapping atmospheric winds and waves and their variability over time, this observatory will directly address this longstanding mystery.

Broad Coverage: Simultaneous spectral coverage from the mid- to the far-IR is another requirement for this observatory, providing access to temperature, aerosol and compositional measurements at the same moment in time. Separation of these measurements causes immense difficulties in the interpretation of these rapidly evolving atmospheres. For example, observations have never been able to simultaneously trace giant planet clouds in the 5-μm window (probing 1-4 bar depths) and the 10-μm and 100-μm regions (0.1-1 bar), whilst also relating them to the visible patterns observed at the cloud tops. Furthermore, dust and ice spectral features are broad and difficult to identify when narrow spectral ranges are used. Modelling a wide spectrum allows us to separate the signal of these ices from thermal and compositional signatures, breaking the degeneracy and yielding significant advances in our understanding of the global cloud morphology and composition. In particular, the observatory will study the cycling of dust in Mars' atmosphere, the triggers of global dust storms and the radiative influence of the particulates. Provided the platform has the necessary stability for ***observations of exoplanetary transits***, the broad spectral coverage beyond 5-μm offers: (i) significant potential to detect NH_3, CH_4, H_2O, CO, CO_2, associated hydrocarbons, nitriles and other exotic species in their atmospheres; (ii) the capability to separate thermal and compositional signatures that would be impossible with narrow spectral ranges (e.g., using the CO_2 band at 15 μm for super-Earths); (iii) access to cooler transiting planets around M stars, whose black body emission peaks at mid-IR wavelengths; and (iv) access to bands of astrobiological significance on super-Earths (e.g., O_3 at 9.6 μm). The spectral coverage also offers the possibility to ***observe brown dwarf atmospheres in the mid-IR***, something that was only previously possible with AKARI (e.g. Sorohana et al., 2012). These results highlighted the lack of knowledge of molecules in the at wavelengths exceeding 3 μm, with NH_3 being weaker than expected, and CO being present in all low-temperature, methane dominated brown dwarfs. This ***broad spectral coverage and tunable spectral resolution offers significant potential for new discoveries for both the planetary and exoplanetary communities.***

Time Domain Science: Planetary atmospheres evolve over a range of timescales, from short-term meteorological variations that can be discerned by cloud tracking, to year-on-year variations (e.g., the life cycles of Jupiter's belts and zones, enormous storms on Saturn) and seasonal variability (Martian hydrological cycle, thermal and compositional asymmetries on the giant planets). The underlying sources of these variations (e.g., latent heat release, injection of material from rising volcanic or atmospheric plumes) remain a mystery due to inadequate time sampling and uncertain causal connections. The extreme conditions found on the ice giants (the large axial tilt of Uranus, and the unusual balance of solar forcing and internal heat emission on Neptune) are of particular importance to our understanding of seasonal processes. Atmospheric features have never been tracked at these wavelengths in continuous movies, and a year-by-year comparison of seasonal changes has never been performed systematically. Furthermore, tracking thermal emission variations as an object rotates (e.g., Titan, Uranus and Neptune) can reveal longitudinal contrasts and their causes (unusual cloud activity, waves, storms, vortices, etc.). Irradiated exoplanets and brown dwarfs both have atmospheres that vary with time, either due to irradiation from their host star, or shifting molecular bands, particularly for objects on the L-T transition (Buenzli et al., 2012). All of these ***time-domain studies require a dedicated platform*** able to revisit targets on multiple occasions over a long mission lifetime, to provide the next stage in our understanding of atmospheric processes across a broad range of astrophysical objects.

Theme III: Surfaces

Key Question: What are the thermophysical properties of primitive bodies (comets, asteroids, TNOs, KBOs), planetary surfaces, rings and satellites in our solar system?

The thermal infrared provides important diagnostics for the conditions to be found on rock-ice objects with tenuous 'atmospheres', such as the icy satellites of the giant planets, or the comae of cometary objects (e.g., Figure 3). The peak of their spectral energy distributions occurs at the longest wavelengths in the far-IR, and the characterization of spectral intensity and slope reveals the temperature of these objects, and their physical sizes from energy balance if the albedo is known. ***Infrared imaging also reveals the physical state of the surface ices and dust*** (e.g., amorphous and crystalline forms provide different spectral

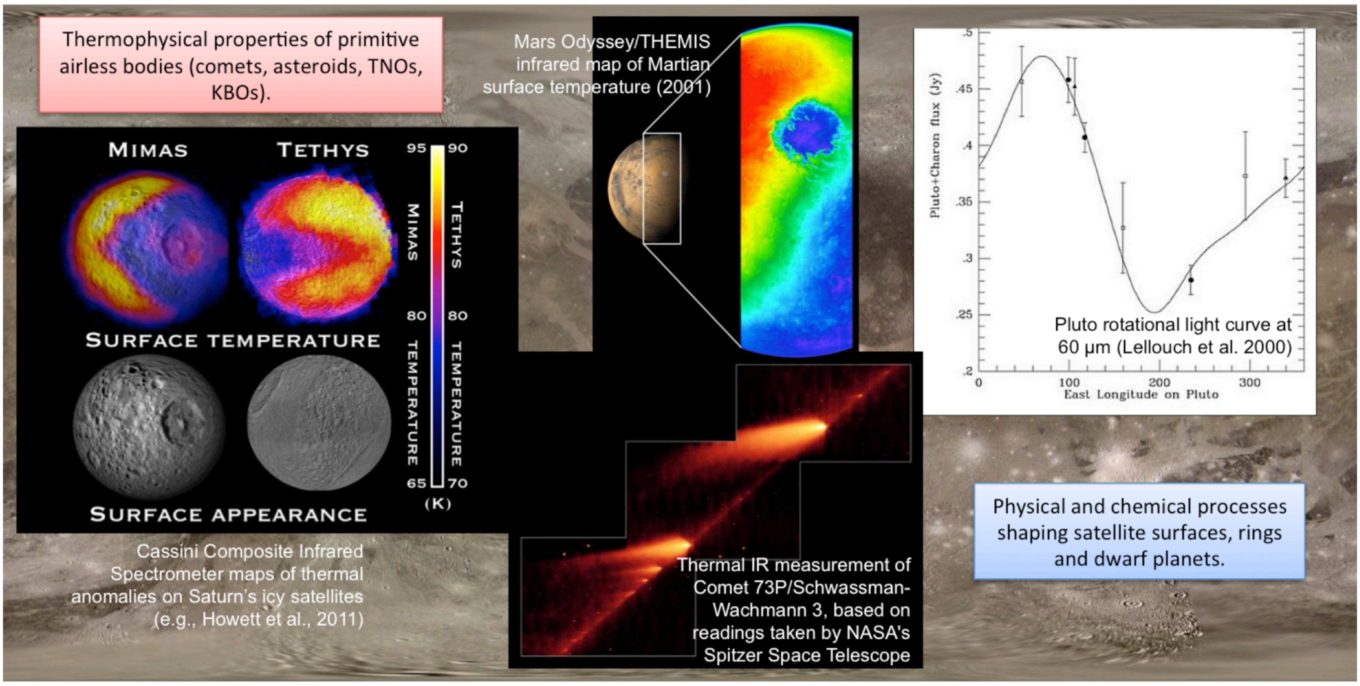


Figure 4 Thermal infrared mapping of comets, asteroids, planetary satellites and dwarf worlds will reveal the thermophysical properties and composition of their surfaces, as well as constraining their energy budgets and identifying the presence of emission variations related to endogenic activity.

signatures in the infrared), and broad signatures can reveal the presence of exotic materials such as organics. Unlike the larger planets that can be spatially resolved, the majority of planetary satellites, asteroids, KBOs and TNOs will be measured as disc-averages. However, measurement of rotational variability can be used to determine spatial contrasts in thermal inertia properties as heterogeneous regions rotate into sunlight (e.g., Lellouch et al., 2000), and place constraints on the physical size of small, unresolved objects. ***Comparing compositional differences between these objects provides insights into their origins*** and the processes responsible for shaping our planetary system.

Comets and Asteroids: Emission from cometary nuclei and their expelled gas and dust tails will be monitored as these objects approach and recede from perihelion, revealing the properties and origins of this primitive solar nebula material and identifying the ices, volatiles (H_2O, CO, CO_2, CH_3OH, etc.), organics and dust production rates and properties. For example, olivine and pyroxene signatures in the dust between 9-35 μm would reveal the fraction of crystalline silicates from the hotter regions of the solar nebula, versus amorphous silicates of a cooler, more distant origin. The importance of the D/H ratio was described in Theme 1, but the spin-state of hydrogen in H_2O also reveals the processes at work during their formation. Furthermore, distinguishing contrasts in the crystallinity of the different dust jets could reveal the inhomogeneity of the nucleus. The cometary inventory of organics - spectrally detected as polycyclic aromatic hydrocarbons (PAHs) between 6-12 μm - will allow us to investigate the ***delivery of organics into the forming terrestrial planets***. All of these parameters will be compared with similar measurements of asteroids (particularly Vesta), main belt comets, and recently identified objects in the asteroid belt that exhibit volatile degassing upon their perihelion passages. This discovery has turned our naïve impression of volatile-rich comets and desiccated asteroids on its head, and could have implications for volatile delivery mechanisms in the early solar system.

Dwarf Planets: There are more than 1500 objects beyond the orbit of Neptune, and although Herschel focused on around 130 targets, a long-lived observatory such as PSIO has the ***potential to discover and determine thermal properties of new objects whilst refining our understanding of those previously observed*** (e.g., the Herschel program for cool TNOs and Plutinos, Müller et al., 2009; Mommert et al., 2012). Thermophysical conditions, shapes, sizes and rotational properties of dwarf planets and KBOs, such as Pluto, Ceres and Eris, could be determined and refined by monitoring their rotational light curves at a variety of infrared wavelengths. Pluto, for example, is believed to have a tenuous CO_2 atmosphere that collapses as surface frosts at aphelion, with a rudimentary atmospheric circulation between summer and winter poles. The atmospheric pressures and densities could be determined from occultation studies, while the heterogeneity of surface thermal inertia and emissivity might be deduced from light curve measurements. The same could be provided for other KBOs and TNOs in the distant solar system to ***assemble reliable statistics on the population, size distributions and environmental characteristics of these worlds***. Their sizes and albedos will be determined from thermal measurements (assuming radiative balance), and potentially their densities and porosities if their gravitational fields can be determined via mutual interactions. The energy balance and thermal inertia will allow us to investigate heat transport mechanisms within asteroidal regoliths of varying densities. Finally, the surface mineralogy (balance of crystalline and amorphous silicates) could be determined via spectral features in the infrared, particularly the ice water hydration band near 3.1 μm.

Satellites: The satellites of the giant planets will be studied in a disc-averaged sense, monitoring their infrared lightcurves as they rotate around their gas giants. With a spectral range covering the peak and tail of the Planck emission, the observatory will use spectral emissivity variations with wavelength to constrain surface composition and water ice grain sizes. Recent thermal-IR studies of the Saturnian satellites have revealed unique ***near-surface heat sources*** (e.g., the tiger stripes of Enceladus) and ***thermal contrasts associated with surface-magnetosphere coupling*** (e.g., the 'Pacman' of Mimas and Tethys, Howett et al. 2011) and ***leading-trailing hemisphere asymmetries*** as these tidally-locked satellites move along their orbits (e.g., Europa, Spencer et al., 1999). Of particular interest is Io, the most volcanically active object in our solar system, and the infrared tracking of gaseous SO_2 lines emitted either from sublimating surface frosts or active volcanism to study the surface distribution. Voyager observed SO_2 bands on Io at 7.4 µm to be enhanced over one of the volcanoes (Pearl et al. 1979), and additional subtle features between 10-20 µm were observed and studied from the ground (e.g., Spencer et al., 2005). Repeated long baseline observations of Io and the other satellites can be used to monitor ***variations in thermal emission caused by endogenic activity and discrete hotspots*** on these satellite surfaces, and to ***constrain the energy budget and extent of tidal heating***, providing the crucial energy source necessary for the habitability of these satellites. Even closer to home, such an observatory could provide global coverage of our Moon, investigating the trapping of volatiles within cold, shaded regions of the lunar surface (e.g., Paige et al., 2010) and the thermal inertia as solar illumination varies with time.

Dust: Finally, thermal-IR imaging could be used to study the variable temperatures with Saturn's broad, dense rings as a function of radial distance and season, and to identify mineralogical signatures of silicate dust, water ice and the various contaminants responsible for giving the rings their colours. Broadband thermal emission from dusty environments could be studied both in our solar system (e.g., zodiacal dust) and in planetary debris discs around other stars, searching for common compositional signatures of dust material throughout our solar system.

Theme IV: Interaction

Key Question: How do solar system objects interact with one another, with the parent star and how do they vary seasonally?

The final theme to be addressed by the observatory is that of time-variable interactions between all of the various bodies within our solar system (Figure 4), allowing us to investigate planetary processes in using the expected long operational baseline (5+ years) of the observatory.

Planet-Star Interactions: Planets interact with their host stars in two ways – via stellar irradiation, causing atmosphere/surface heating and sparking photochemistry; and via solar wind plasma interacting with their extensive magnetospheres. The latter is most evident in the infrared at the poles, where charged particles accelerated into the upper atmosphere generate dramatic auroral light shows and can lead to unusual chemistry at high latitudes. Planetary aurorae interact with many factors, including the IMF direction (interstellar magnetic field), the presence of internal plasma sources and the solar wind pressure, so auroral monitoring can be used as a proxy for studying the balance between solar wind and internal plasma source activity at work within planetary magnetospheres. Planetary aurorae and ionospheric winds will be mapped in H_3^+ emission near 3.4-3.6 µm (and possibly fluorescence of other molecular species), showing how the morphologies of auroral ovals shift in shape and intensity in

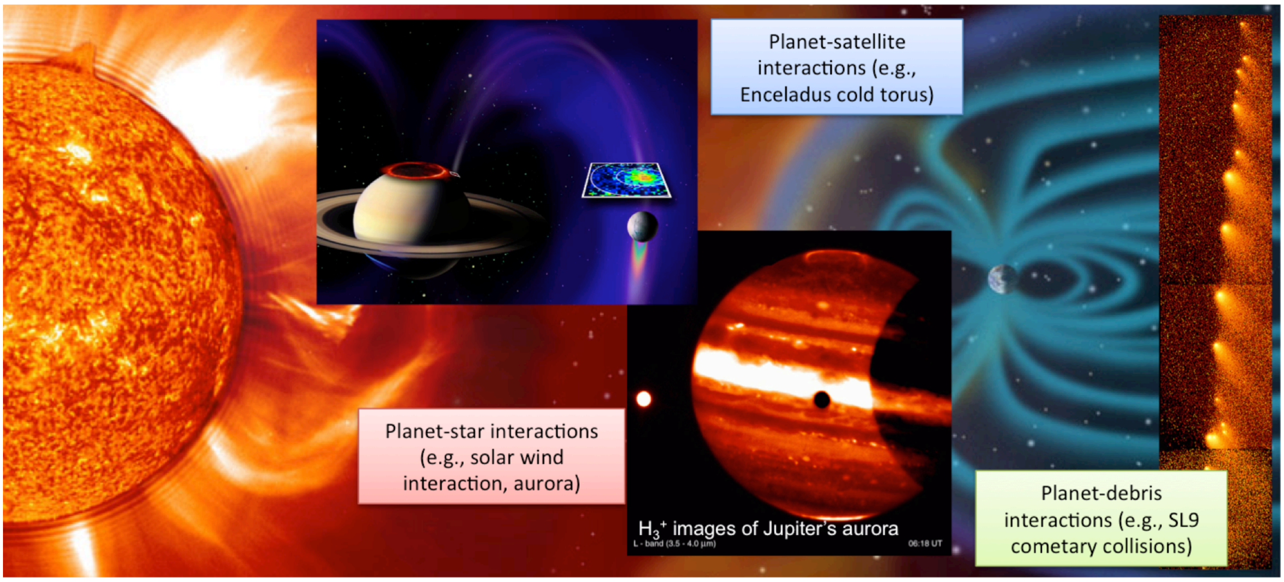


Figure 5 Long-baseline monitoring of solar system targets can be used to understand their complex interactions, both with the Sun and within each planet-satellite-ring system. Cometary impacts, planetary upper atmospheres and aurora will be of particular interest to PSIO.

response to the varying solar wind pressure and other factors. Such H_3^+ mapping of the giant planets allows studies of thermospheric temperatures, gaining insights into the high-temperature 'energy crisis' described in Theme 2 as well as probing seasonal variability, upper atmospheric winds/circulation and the strength of the magnetic field. If coupled with near-simultaneous observations of H_2 emission near 2 μm (extending below the present arbitrary 3-μm cut off for PSIO), this would also allow us to estimate the auroral electron energy in addition to the temperature to enable us to study the coupling between the solar wind, magnetosphere and ionosphere (e.g., Tao et al., 2012). Furthermore, the high thermospheric temperatures determined at wavelengths near 4 μm will be directly correlated with stratospheric 'hot spots' observed in the 7-14 μm range in hydrocarbon emission. The high sensitivity of an infrared observatory might also allow the first detection of H_3^+ emission from Neptune (e.g., Melin et al., 2011), and will certainly enhance studies of all the giant planets by ***performing invaluable remote magnetospheric and ionospheric science via continuous 'real-time' auroral monitoring over several planetary rotations.***

The effects of the seasonal variability of sunlight will be investigated on all planetary surfaces and atmospheres over a long mission baseline. For example, the near-IR reflectance of Neptune shows unexplained correlations with the degree of solar activity (e.g., Lockwood and Jerzykiewicz, 2006), possibly due to albedo effects in the clouds, so monitoring how planetary atmospheres respond to solar cycle variations could reveal new unforeseen interaction mechanisms. Thermal and compositional mapping of Saturn and Titan will ***track the evolution of hemispheric asymmetries driven by seasonal heating and photochemical patterns***, extending our understanding of seasonal processes in the Saturn system long after the conclusion of the Cassini mission.

Planet-Satellite Interactions: Visiting spacecraft have revealed that giant planet satellites are depositing significant quantities of material into the magnetospheric plasma environment. Torii of plasma are deposited in the wake of these satellites, notably Io and Enceladus, and these torii can interact with the planetary atmosphere, producing 'footprints' in the auroral ovals and transferring dust and ice to 'rain down' on the atmosphere at locations governed by the magnetic fields. The water ice materials being actively vented by fissures on Enceladus create a cold torus orbiting Saturn that absorbs the infrared emission from Saturn's stratosphere (discovered in the far-IR by Herschel, Hartogh et al., 2011). Furthermore, the tidal forces keeping the satellite interiors in a fluid state vary as a function of radial distance from the gas giant, and the thermal balance on these satellites will provide estimates of the efficiency of tidal energy deposition. These ***interactions between planets and their satellites serve as laboratories for planetary system processes on a variety of scales***.

Planet-Debris Interactions: Finally, planets continue to interact with the debris (comets, asteroids and interplanetary dust) left over from the epoch of planetary formation. Planetary impacts, such as Shoemaker Levy-9 in 1994 on Jupiter (Harrington et al., 2004), create debris fields that persist for many weeks post impact, and chemical perturbations that can last for years (e.g., HCN and CO on Jupiter). Fast et al., (2002) studied the temporal behaviour of ammonia lofted into Jupiter's stratosphere by the SL9 collision using high-resolution mid-IR spectroscopy. The thermal properties, chemistry and mineralogy of those debris fields have direct relevance to airburst explosions in Earth's atmosphere, and can only be investigated in the thermal infrared with an agile and flexible platform. Interplanetary dust also rains down on these planets, contributing oxygenated species (CO, CO_2, H_2O) into the upper atmospheres of planets that can be detected via stratospheric emission lines (e.g., Moses et al., 2000). Thus ***the planets are fundamentally linked to the host star, the satellite system and the wider interplanetary space*** via a variety of processes that could be investigated by this observatory.

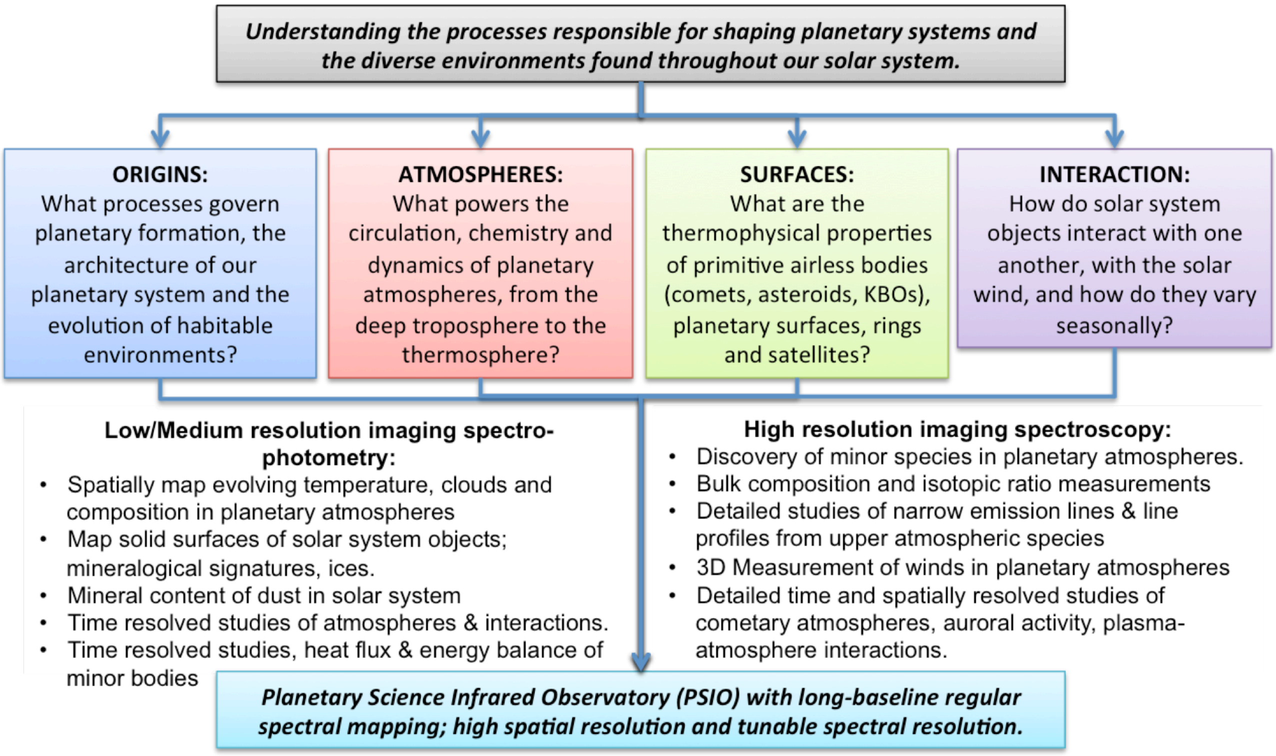


Figure 6 Outline of the four themes to be addressed by a dedicated planetary science observatory, showing the flow from our top-level science question, to the four themes and a subset of specific objectives for PSIO.

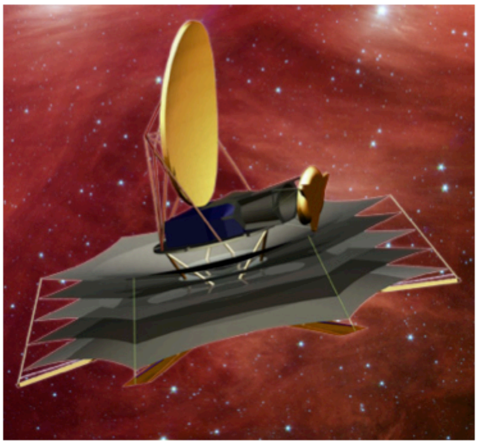
4. Observatory Architectures

We summarise the four science themes for understanding the processes shaping our planetary system in Figure 5. To address these objectives, we advocate an observatory class mission, providing imaging spectroscopy at moderate ($R{\sim}10^3$) resolution over an arcmin FOV; and heterodyne-level resolution ($R{>}10^6$) in selected mid-IR and far-IR bands to probe planetary regimes not previously explored. Spatial resolution must be sufficient to resolve contrasts across the discs of Venus, Mars, Jupiter and Saturn, suggesting a 3.5-5 m monolithic mirror or a distributed array for longer wavelengths. The observatory must be flexible and agile to respond quickly to new events, and must be capable of devoting significant time to single targets to advance time-domain science within our solar system. If possible, the observatory should be stable enough to address ancillary science of exoplanets, brown dwarfs and planetary discs, although we recognise that no single mission architecture will be capable of addressing the four science themes equally. The science requirements for an infrared planetary observatory break into two distinct categories as shown in Figure 5: low to medium resolution spectrophotometry and very high-resolution spectroscopy.

Possible mission architectures

Two basic mission architectures present themselves: a single monolithic mirror passively cooled to space and a distributed array of smaller dishes structurally connected to synthesise a large aperture through interferometry. The ***monolithic mirror concept*** could either be a Herschel or a non-actively cooled SPICA type on-axis Cassegrain telescope; or a Planck style off axis telescope. While there is much design heritage with on-axis telescopes, their size is limited by the need to fit them into a launch vehicle fairing – 3.5 m is currently the largest that can be accommodated. With an off-axis design the physical area can be made larger using an elliptical primary as illustrated by the JPL SAFIR concept shown in figure 6. A 10-m design requiring cooling to <10 K is shown, but a planetary observatory would not require this degree of cooling and both the dish and the Sun shields would be considerably smaller. A 5-m off-axis design would provide spatial resolutions such as those listed in Table 1.

At longer wavelengths where the resolution offered by a single dish is insufficient, the idea for a ***structurally connected small dish array*** stems from heterodyne spatial interferometers successfully operating on Earth. As well as the very large sub-mm ALMA instrument, there are two other instruments of interest: the Sub-Millimeter Array (SMA) on Hawaii operating at ~100s GHz and



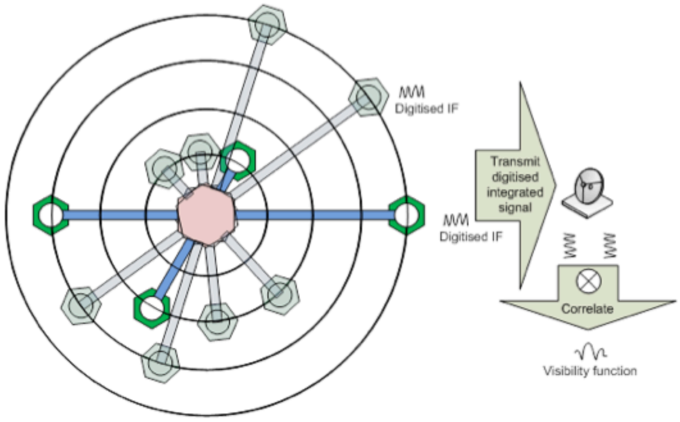


Figure 6: Left: The JPL SAFIR concept for a cooled off axis 10 m dish, taken for the SAFIR study website. Right: A possible concept for a distributed spatial interferometer array. This is shown in plan view with four small receivers deployed on booms from a central hub. The deployed elements have a ~1 m antenna with heterodyne mixer technology receivers centrally phase locked. The whole satellite is rotated sweeping out a partially populated uv plane as indicated by the light grey and the solid circles. The spatial correlation could be achieved either through a correlator placed on the central spacecraft or by digitising the spectrum from each receiver, time stamping it to high precision and telemetering the result to the ground – similar to a VLBI radio system.

the Infrared Spatial Interferometer (ISI) on Mount Wilson operating in the 10 μm atmospheric window (Hale et al., 2000). Both instruments use heterodyne receivers with distributed phase locking systems for the local oscillators. A similar arrangement could be achieved in a structurally connected array of small dishes operating in space. An outline concept is illustrated in figure 6 where ~ 1m dishes are deployed on extendable booms around a central hub spacecraft. The whole satellite is then rotated and a large aperture is synthesised. Deployable booms up to 5 m have been demonstrated on various missions and the small nature of the dishes, combined with the use of heterodyne receivers, reduces the necessity for low temperatures at the deployed receivers. The advantage of heterodyne spatial interferometers is that phase knowledge is a natural consequence of the detection technique provided the local oscillators are phase locked. Various methods of phase locking can be contemplated, the easiest being the distributed phase lock signal already used in ISI, SMA and ALMA. In the MIR, this concept also obviates the difficult task of optical correlation and use well known RF techniques instead. For the local oscillators themselves, new technology is available or being actively developed for low power low mass LOs working at 100s-GHz (photonic mixers) to supra-THz (Quantum Cascade Lasers, QCLs) which have demonstrated performance from ~2.5 THz up to 30 THz. No moving parts are required apart from the deployment booms and the technique of phase closure could be used to eliminate variations in path differences due to any motion of the booms during observations. While a multiple dish interferometer working at THz represents a challenging mission but would give the chance to provide far-IR spatial resolutions to match the mid-IR (Table 1) and most, if not all, of the technology required is under active development.

Instrument options

For the imaging spectro-photometer several instrument options are possible ranging from an Integral Field Unit (IFU) grating spectrometer such as the PACS instrument on Herschel, an imaging Fourier Transform Spectrometer (iFTS) like the SPIRE instrument on Herschel or a broad band imaging radiometer using dichroic and filter chains to define fixed bands. For the high-resolution system the only extant options in the sub-mm and FIR are heterodyne receivers. For the MIR one could envisage an immersion grating type spectrometer or a heterodyne system. In the NIR an immersion grating might also be used. For all wavebands an alternative might be to use Spatial Heterodyne Spectrometers (SHS), which are a form of high-resolution static FTS utilising gratings in a beam splitter arrangement.

Spectro-Photometer: Our preferred option for the spectro-photometer is to use an iFTS. With an FTS, the beam splitter and choice of detector limit the spectral range and the spectral resolution is programmable based on the maximum achievable path difference in the instrument. With flight development programmes for beam splitters made of extremely broadband materials such as diamond now well advanced (e.g. the OTES instrument currently in development for NASA's OSIRIS-REx asteroid sample return mission) a single instrument can provide spectral coverage from the near-IR (e.g. 1 μm) to greater than 100 μm at moderate resolution (e.g., >2 cm^{-1}) using broadband bolometer-type detectors. Depending on the detector configuration these instruments can also be used to provide a basic imaging capability. Spectral range for higher resolution instruments is typically limited by the requirement for cooled detectors, usually based on Mercury Cadmium Telluride (MCT). By using cooled (e.g. <80 K) detectors spectral resolutions of < 0.1 cm^{-1} are routinely achieved by Earth Observing instruments. For example, the MIPAS instrument on ESA's highly successful ENVISAT was a 320 Kg instrument with an unapodised spectral resolution 0.035 cm^{-1} and spectral coverage from 4.15 – 14.6 μm. A notable example of an FTS used in planetary science is the Cassini Composite Infrared Spectrometer (CIRS), which has operated continuously in Saturn orbit for almost a decade covering 7-1000 μm.

High-Resolution: For the high-resolution instrument we would propose that heterodyne technology is used for the FIR and MIR wavebands. The most challenging channel for this is the MIR. In this band there is on-going development of laser heterodyne spectroscopy that has been widely used from the ground for both Earth's atmosphere (Weidmann et al., 2011) and planetary atmosphere observations (Mumma et al., 1981; Kostiuk et al., 2005). The advent of MIR QCLs has enabled a far greater flexibility in terms of LO. QCLs are readily available to cover from 4 to 12 μm and current MIR QCL technology is applicable to devices up to 20 μm for high temperature continuous wave operation. If cooled to 80-100 K, QCLs can operate down to ~2THz. QCLs have been space qualified by NASA JPL (e.g., MSL and CLARREO).

In the future, MIR and FIR heterodyne spectrometers would clearly benefit from ***advances in local oscillator (LO) and mixer technology.*** On the LO side, improving the frequency agility while keeping laser spectral purity and phase locking combined monolithic design would be desirable to enhance flexibility. Several options include Continuous Wave optical parametric oscillators, high power difference frequency generation, and broadly tuneable QCLs with coverage up to 400 cm^{-1} have been demonstrated. The latter would require monolithic tuning mechanism through microelectromechanical systems devices or MIR acousto-optical tunable filters. Monolithic frequency comb generators in the NIR are also under development, which have utility in phase locking QCLs over a wide waveband when combined with photonic mixing elements. Development of QCLs at wavelengths greater than 12 μm would also be desirable and, for THz applications the development of higher operating temperature devices is also required.

Mixer technology represents another development

Parameter	Spectro-photometer	High Resolution Spectrometer
Spectral Resolution (λ/Δλ)	Low res (LRS) ~5-10 Med res (MRS) ~100-1000	HRS ~ 10^6 (≡ 15 m/s)
Spectral coverage	LRS at least to 200 μm MRS 3 – 30 μm	Three bands at: **NIR (3-5 um)** CO, H_3+, H_2O, NH_3, PH_3 and other minor species. **MIR (~10 um):** NH_3, PH_3, CH_4 and higher hydrocarbons, HCN and nitriles, oxygenated species. **FIR/sub-mm (~THz)** – H_2O, CH_4, OH, CO + isotopes
Instantaneous Spatial Coverage	40-50" (Jupiter)	Single pixel only required – array receiver desirable
Spatial Resolution - equivalent aperture	3.5 m required for MIR 5 m desirable for MIR For >100 μm larger baseline required (See Table 1)	At NIR and MIR same as spectrophotometer For THz longer baselines (>10 m) may require distributed array
Sensitivity limiting case	KBOs – require 10's μJy in MIR and 0.5-1 mJy at >50 μm Planets do not require very high sensitivity	As long as system is stable NETDs ~10s K
Time Resolution	Typically hours to days and weeks to track variation over all timescales. Rarely some events occur on timescales of minutes	
Mission Duration	Minimum 5 years; 10+ years desirable to track seasons in outer Solar system	

Table 3 Instrument options for PSIO.

challenge. The most efficient MIR mixers have been based on MCT photodiodes. Specific technological development towards high heterodyne efficiency, higher speed to extend the spectral multiplexed coverage, and higher saturation level to benefit from high power LO would ***greatly enhance the capabilities of MIR heterodyne spectrometers***. The availability of high power LOs would also open the path to heterodyne imaging through the development of mixers' arrays. Current MCT photodiodes cut off after 11-12 µm, so specific development for longer wavelengths is required. Alternate technologies for MIR mixers are more far reaching but may provide solutions. MIR hot electron bolometer (HEB, graphene-based), transition edge bolometer, Metal Insulator Metal or Metal oxy Metal diodes using plasmonics have started to be developed. HEBs and SIS mixers are commonplace in the sub-mm band (the Herschel HIFI instrument for instance) but require liquid helium type cooling for their operation. These devices also do not work at supra-THz frequencies where Schottky diodes represent the only viable option to date. Whilst a mixture of these technologies may be sufficient for the needs of planetary observation, it is clear that such an observatory would benefit greatly from enhanced performance and/or higher operating temperatures for mixers across the THz band.

Orbital mission configurations

For both the monolithic and array architectures, the most obvious choice of orbit is to place the observatory at L2 like Herschel, Planck and JWST. This will provide an extremely stable thermal environment allowing the telescope to cool passively to below 40 K. In the case of the PSIO this will be especially stable, as the observatory will only be required to point within about +/- 10 degrees from the ecliptic plane. This will allow observations of all the planets except Mercury, Venus and the Earth. Whilst only providing a limited view of comets as they approach the Earth, this should be sufficient for most purposes. An alternative, and more radical, mission would be to place the satellite into Solar orbit towards either L4 or L5. The telescope could be pointed at an oblique angle with respect to the Sun allowing observation of Venus, the Earth, near Earth objects and comets as they approach the Sun. Whilst this would be a less favourable thermal environment, with possibly a warmer telescope, it would provide a unique mission concept allowing ground-breaking observations of the inner Solar system in the infrared band.

Required Technology Roadmap

Whether or not one of the proposed mission architectures is selected, there are a number of technology developments required that would benefit not only a remote sensing observatory but also future planetary missions in general. We list the most significant ones here:

Imaging spectrophotometers: High temperature (>30 K) NIR/MIR detectors; Static iFTS designs for NIR/MIR; and broad-band immersion gratings for NIR/MIR
THz and supra-THz heterodyne receivers: Low power compact LOs such as photonic mixers and QCLs; Receiver arrays; high temperature mixers; and low power fast digital spectrometers.
Mission architecture: Lightweight large area passively cooled telescopes; spatial interferometer systems design; systems design for long duration (10+ year) missions; and backup low power highly compact mechanical coolers.

5. Conclusion

A step change in our understanding of planetary origins and the evolving environments of our solar system ***requires a dedicated observatory to advance the field of time-domain planetary science*** in a way that snapshot observations (e.g., JWST and SPICA) cannot. Uninterrupted infrared monitoring without the need to remove the contamination of our own atmosphere will reveal the processes at work on solar system objects in all their guises, from the smallest planetary building blocks to the largest planets of our solar system.
The combination of broad spectral coverage; tunable high-resolution spectroscopy in selected channels; a spatial resolution approaching that of JWST and an ***observatory optimised for longevity*** would make PSIO a unique platform for solar system science. The observatory configurations and technology roadmap outlined above ***represent significant advances in infrared astronomy beyond the themes covered by this paper*** (e.g., exoplanet science in the habitable zone; brown dwarfs; discs and nebulae, etc.). While no single mission can achieve all of the science goals outlined here, we advocate the inclusion of infrared observations of solar system targets in any of ESA's future cornerstone missions, and development of the critical detector, heterodyne receiver and telescope technologies required to meet the aims of PSIO.

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