The Far-IR View of Star and Planet Forming Regions

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ABSTRACT

The far-IR range is a critical wavelength range to characterize the physical and chemical processes that transform the interstellar material into stars and planets. Objects in the earliest phases of stellar and planet evolution release most of their energy at these long wavelengths. In this contribution we briefly summarise some of the most relevant scientific advances achieved by the *Herschel Space Observatory* in the field. We also anticipate those that will be made possible by the large increase in sensitivity of *SPICA cooled* telescope. It is concluded that only through sensitive far-IR observations much beyond *Herschel* capabilities we will be able to constrain the mass, the energy budget and the water content of hundreds of protostars and planet-forming disks.

1. INTRODUCTION

Modern astrophysics is just beginning to provide answers to some of the most basic questions about our place in the Universe: Are Solar Systems like our own common among the millions of stars in the Milky Way and, if so, what implications does this have for the occurrence of planets that might give rise to life? The basic building blocks of a planetary system, gas and dust, emit efficiently at mid- and far-IR wavelengths (~5 to 350 μm), a critical domain in which to unveil the processes that transform the interstellar material into stars and planets.

Due to the atmospheric opacity, the far-infrared domain (~30–350 μm) has been one of the last spectral windows used in astrophysics. Indeed, observing at these long wavelengths with sufficient angular resolution and sensitivity represents a significant technological challenge that requires space telescopes equipped with sophisticated cryogenic instrumentation (down to a few mK) and very sensitive detector arrays.

The far-IR domain begun to be fully exploited by the NED/UK/NASA's *IRAS* telescope and the ESA's *Infrared Space Observatory*, *ISO*. It has been successfully continued by NASA's *Spitzer*, JAXA's *AKARI* and most recently by the very successful *Herschel Space Observatory*, the largest telescope ever launched to space and a cornerstone mission of ESA with science instruments provided by European-led Principal Investigator consortia and with participation from NASA (Pilbratt et al. 2010).

Observations with the above space telescopes revolutionised our understanding of where and how stars are born. Objects in the early phases of star formation (SF), and in the first stages of planet formation (protoplanetary disks) release most of their energy in this domain. The far-IR range provides key spectral diagnostics physical conditions (atomic fine structure lines, high-J CO lines, etc.), chemical evolution (water and light hydrides), dust composition (minerals and ices) and dust column density. Therefore, observing in this critical domain we can constrain the mass of protostars and planet-forming disks, access to their most important gas cooling lines and ultimately, understand their nature and predict their evolution.

The power of *SPICA*, a large single-dish *cooled* telescope with unprecedented sensitivity, broadband coverage and large field-of-view, will drastically improve our understanding of the star and planet formation processes (at small spatial scales), its environment, and its link to galaxy evolution (SF at large scales). In order to progress in these fields, SED mapping of large areas of the sky, as well as more detailed spectroscopic studies of large samples of young stellar objects (YSOs) at sensitivities well below those achieved by *Herschel* are clearly needed. In this context, only a very sensitive instrument covering the critical "far-IR gap" (*e.g.,* SAFARI) will be able to characterise the objects and the environments that are too obscured for the the *James Webb Space Telescope* (*JWST*) to examine in the mid-IR, or too warm and extended to be efficiently observed by the the *Atacama Large Millimeter/submillimeter Array* (ALMA).

2. LESSONS FROM *HERSCHEL* AND THE NEED TO GO BEYOND

In this contribution, we summarise some of the most important achievements of *Herschel* in the field of star and planet formation. This review is necessarily incomplete and descriptive. The goal is to present some areas where *Herschel*, by observing in the far-IR, has made unique contributions. We will conclude by discussing its limitations and how only a *cooled* telescope like *SPICA* will push the frontiers of our knowledge.

2.1. The Filamentary Structure of the ISM

Herschel's photometric cameras had the ability to map several square degrees in the 70/100/160 μm (PACS) and 250/350/500 μm (SPIRE) bands. *Herschel* images confirmed that nearby interstellar clouds are systematically structured in networks of filaments, the *universal filamentary structure* of the ISM (*e.g.,* André et al. 2010; Molinari et al. 2010). These filaments are reminiscent of the structures found in large-scale magneto-hydrodynamic turbulence simulations of the ISM (*e.g.,* Padoan et al. 2001). The structure and properties of the diffuse ISM provide the initial conditions for the formation of dense giant molecular clouds (GMCs) where stars are born. The physics that governs the large- and small-scale structure of such diffuse clouds is a complex interplay between magnetic fields, turbulence, gravity and thermodynamics.

Herschel has provided spectacular large-scale images of diffuse clouds before the onset of SF, including high latitude clouds like the Polaris Flare (Miville-Deschênes et al. 2010). They unambiguously reveal the filamentary and clumpy structure of the ISM down to spatial scales of ~0.01 pc (10″ angular resolution for a source at ~200 pc or ~0.1 pc for a source at 2 kpc). Sensitivity and high imaging speed in photometric mode were the key instrumental attributes of *Herschel* photometric cameras.

Studying the morphology of a few hundred filaments, most of them regions with on-going SF, the team of P. André et al. concluded that these filaments have the same characteristic width (~0.1 pc; Arzoumanian et al. 2011). Although their origin is not fully understood, this scale corresponds to the same scale below which turbulence becomes subsonic in diffuse, non-star forming gas. These findings clearly connect the fundamental properties and structures of the ISM with the regions where stars form.

2.2. From Filaments to Cores

Far-IR photometric surveys of nearby clouds further indicate that cold prestellar cores form primarily along dense filaments as they fragment (*e.g.,* André et al. 2010; Molinari et al. 2010). From the observational point of view, prestellar cores are detected in lines of sight where the column density of material is above a given A_V threshold (roughly above 8 magnitudes of extinction). With a knowledge of the dust properties and of the dust-to-gas conversion factor, one can translate the observed far-IR and submm continuum luminosities into total masses. *Herschel* observations show that despite of their relevance (prestellar cores collapse gravitationally and form stars) only ~2 % of the cloud mass is in these cores. The "gas to stars conversion" is far from being an efficient process. Therefore, most of the cloud mass, ~85 %, is contained in the extended component at lower extinctions ($A_V < 8$ mag). These more diffuse regions are dominated by the interstellar turbulence, magnetic field and UV-irradiation. These results also mean that understanding and characterising observationally the extended component of GMCs at large scales has a great relevance.

By studying the mass distribution of the observed prestellar cores, the *Herschel* teams were able to plot the so called "core mass function" (CMF). The CMF appears to resemble the stellar initial mass function (IMF) of stars (meaning of course that stars form from cores). Yet the CMF is: (1) shifted towards higher masses by a factor of ×3 and is not well sampled down to masses corresponding to the mean mass of the log-normal IMF (<0.3 M_{Sun}) and into the brown dwarf regime (*e.g.,* Hennebelle & Chabrier works). Improved sensitivity in the far-IR domain will be critical to cover this important stellar population (the most numerous) and to fully understand the origin of the IMF.

Far-IR observations are extremely important to understand the first stages of protostellar evolution. In particular, they are critical to search for the "holy grail" of SF, the so-called *first hydrostatic cores* (FHSC). Prestellar cores are thought to collapse isothermally until become dense and opaque. At this point, the radiation of the central object gets trapped and the gas is heated up to ~2000 K. At these temperatures, molecular hydrogen (containing the bulk of the core mass) starts to be dissociated (see *e.g.,* Commerçon et al. 2012). This is a crucial but short-lived (~10^2–10^3 years) evolutionary stage towards the formation of a Sun-like star. FHSCs are rare objects and thus they are difficult to identify without mapping very large areas of several SFRs. For nearby SFRs, FHSCs should be visible at 70 μm (*e.g.,* with *Herschel*) but not at 24 μm (*e.g.,* with *Spitzer*). FHSCs have a peculiar SED not compatible with a single cold grey-body (like that of a starless/prestellar core) nor with more evolved SEDs of Class-0 protostars. *Herschel* observations of the B1-bs core in Perseus have shown that this is a good FHSC candidate (Pezzuto et al. 2012). Broad-band far-IR and submm observations over entire SFRs are clearly needed to improve the number of detections.

2.3. From Deeply Embedded Protostars to Protoplanetary Disks

Understanding the physical processes involved in the earliest stages of stellar evolution requires to study the heating and cooling mechanisms that take place in YSOs. Beyond photometry, far-IR spectroscopic observations can uniquely probe the evolution of the physical and chemical structures in YSOs, from warm protostellar envelopes and their outflows to planet-forming disks around young stars (*e.g.,* van Dishoeck et al. 2011).

The evolutionary sequence from Class-0 to Class-II protostars is characterised by strong changes in the physical conditions (density, temperature, ionisation...), with the gas composition and excitation changing accordingly. Protostellar evolution is complicated and it is not fully understood. The detection of the most important coolants of the warm/hot gas in YSOs (H_2, high-J CO, H_2O and O) allows a quantitative determination of the energy budget in these objects. Complete far-IR spectral scans of embedded protostars with *Herschel* show very rich spectra, with more than a hundred

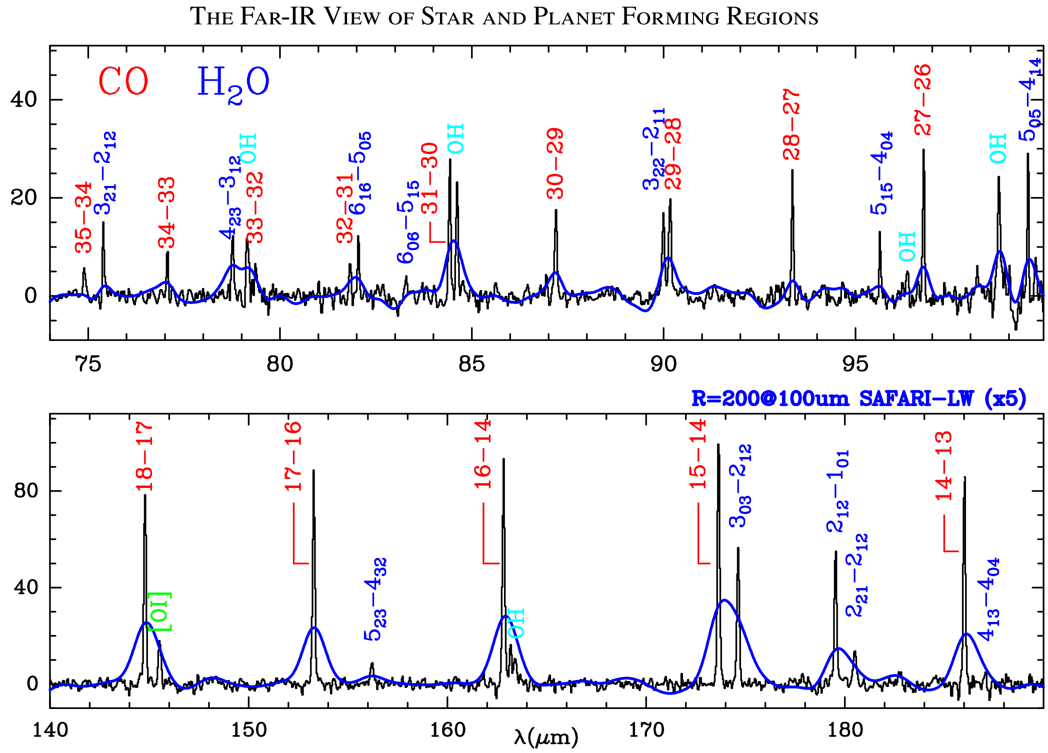

Figure 1. Far-IR continuum-subtracted spectrum of the Class 0 protostar Serpens SMM1 taken with *Herschel*/PACS (Goicoechea et al. 2012). The blue spectrum shows the same spectra as it would be observed in a "fast" low-resolution mode with SAFARI (R~200 at 100 μm). A complete spectrum (~34-210 μm) over a FoV of 2′×2′ could be obtained by SAFARI in only ~30 sec (~3 h and worse sensitivity with PACS). A higher spectral resolution spectrum (similar to PACS) and better adapted for the observation of planet-forming disks, can be obtained by SAFARI in ~4 min.

lines detected even at medium spectral resolution (Goicoechea et al. 2012, see Figure 1) and with a SED peaking in the far-IR. In combination with mid-IR spectra, the entire IR domain is the key piece to characterise the envelope, outflow and disk emission (Herczeg et al. 2012). The far-IR range is uniquely well suited for the detection of tens of lines from warm water vapour and to detect water ice features (44/62 μm bands). Following the water abundance from prestellar cores to planet-forming disks is specially relevant, both as a unique diagnostic tool of the physical conditions in warm/hot gas and also as the key molecule to define the potential habitability conditions later in planetary systems.

Detailed models of the far-IR atomic and molecular lines have been used to characterise the main heating mechanisms in YSOs: shocks, X-rays, UV radiation, etc. (*e.g.,* van Kempen et al. 2010). Unfortunately, owing to the large integration times required to cover the complete far-IR range, *Herschel*/PACS has only been able to spectroscopically characterise a small sample of bright protostars (*e.g.,* Karska et al. 2013; Manoj et al. 2013; Green et al. 2013). Besides, only for a very few YSOs, these objects have complementary mid-IR spectra (from *Spitzer*). The above limitations have prevented a more global characterisation of SFRs with a much larger statistical meaning.

2.4. **The Formation of Planetary Systems**

Planets form in the accretion disks that develop during the collapse and infall of massive protostellar envelopes (~10,000AU) where stars are born. In this context, the formation of planetary systems can be seen as a *by-product* of the SF process. However, we still don't fully understand how young gas-rich protoplanetary disks evolve into planetary systems. Circumstellar disks are very faint, so far difficult to study spectroscopically. Hence, we still have a very incomplete understanding of the formation mechanisms responsible of the great diversity of extra-solar planetary systems detected so far, and of the peculiar features of our own Solar System. These, of course, ultimately include the formation of Earths-like rocky planets with significant liquid water to support life.

The basic building blocks of any planet-forming disk (gas and dust) radiate predominantly in the far-IR band. Key spectral line diagnostics such as warm water vapour, HD, atomic oxygen or dust features can only be observed in this domain. For the first time, *Herschel* reached the sensitivity to carry out far-IR spectroscopy in a few bright protoplanetary disks (*e.g.,* Thi et al. 2010; Fedele et al. 2012; Meeus et al. 2012). Interesting detections include the discovery of significant reservoirs of both cold and warm water vapour in planet-forming disks (Hogerheijde et al. 2011; Riviere-Marichalar et al. 2012). Together with the detection of [O I] 63 μm (the brightest line in disks), much more sensitive detections of water (vapour and ice) in hundreds of disks are needed to fully understand the processes that drive the position of the *snow line*, and thus the mechanisms that lead to the formation of rocky versus gaseous planets.

Molecular hydrogen is the most abundant gas species in protoplanetary disks (containing ~90% of the initial disk mass). However, H_2 is a symmetric molecule and it does not emit radiation efficiently. Instead, the deuterated isotopologue, HD (with its lowest rotational transitions at 112, 56 and 37 μm – not observable with JWST or ALMA) turns out to be the most powerful tracer of the disk total mass. Depending on the excitation conditions, the far-IR lines of HD can be many times more emissive than those of H_2. The only *Herschel* detection of HD (J =1–0 line at 112 μm) towards TW Hydrae disk is a major discovery and implies a disk mass of more than 0.05 solar masses (Bergin et al. 2013). This is enough to form a planetary system like the Solar System despite the advanced age of TW Hya (~10Myr). Indeed, HD is also an important constituent of Jupiter-like giant planets and it is also present in the atmospheres of Uranus and Neptune (Feuchtgruber et al. 2013). The detection of HD towards the closest protoplanetary disk (at ~60 pc) required 7 h of integration time and pushed the detection limits of PACS. A factor ~10 better line sensitivity will be needed to detect HD lines in protoplanetary disks at the distance of the closest SFRs. This will allow us to carry out a unique survey of disks with SAFARI and accurately constrain the mass of a statistically significant sample of planet-forming disks in different SFRs.

3. *SPICA*, A NEW GENERATION FAR-IR COOLED SPACE TELESCOPE

While the very successful *Herschel* mission demonstrates that only in the far-IR we can answer fundamental questions on the star and planet formation processes, *Herschel* has only shown the tip of the iceberg. This conclusion specially applies to the spectroscopic characterisation of YSOs and disks. The number of objects studied was clearly limited. Besides, the *Herschel* telescope was passively cooled to ~80 K, thus only offering a modest increase in sensitivity compared to previous facilities in the far-IR range. The lack of sensitivity and of spectrometers designed to carry out large-mapping also precluded the spectroscopic characterisation of ISM clouds and SFRs globally.

In order to better explain the need for a new, much more sensitive telescope, one has to take into account the capabilities and scientific merit of the major astronomical infrastructures of the next decade. In ~2025, ALMA will be in full operations, providing very high angular and spectral resolution observations in the submm and mm domains. ALMA will resolve the inner structures and the outflows of YSOs and it will observe planet-forming disks in great detail, being more sensitive to the low excitation molecular gas. ALMA, however, will not have access to the most important cooling lines of the warm/hot gas (high-J CO, H_2O, [C II], [O I], ...), it will not observe YSOs at their SED peak and it cannot observe mineral and ice features (the basic ingredients of a planetary system). Also important, ALMA is inefficient for large-scale mapping.

JWST will provide a major increase in angular resolution and sensitivity in the mid-IR domain, but JWST only covers the λ<28 μm range. Hence, it does not cover the critical far-IR band. Besides, it does not provide a high spectral resolution spectrometer in the mid-IR. Finally, JWST is not designed to have a coronagraph with spectroscopic capabilities to characterise young exoplanets *directly*. In the next decade, ELT and TMT-type optical and near-IR telescopes will also be built. Owing to the extinction at these short wavelengths, the regions where stars form will remain obscured.

After *Herschel*'s end of mission, windows of the far-IR domain will be still available for SOFIA stratospheric observations. However, the angular resolution and the sensitivity is not better, and key molecules like H_2O cannot be observed. All in all, it is clear that a very sensitive telescope is needed to cover the critical far-IR wavelength range between JWST and ALMA. In order to go significantly beyond *Herschel* capabilities, such a space telescope needs to be specialised both in large-scale spectral mapping and in providing detailed spectroscopic characterisation of individual YSOs and disks (*i.e.,* observe faint lines, a few 10^{-19} W m^{-2}, on top of a ~0.1–10 Jy continuum).

3.1. *SPICA* Observations of Star and Planet Forming Regions

SPICA's large and cold aperture (~3.2 m at <6 K) will provide a two order of magnitude sensitivity advantage over current far-IR facilities. In combination with a new generation of highly sensitive detector arrays, the low telescope background will allow us to achieve sky-limited sensitivity over the far-IR range. In its current design, the SAFARI instrument covers the far-IR band with a large, fully-sampled field-of-view of $2'\times2'$, both in photometry (48, 85 and 160 μm) and in spectroscopy (~34–210 μm). The angular resolution of *SPICA* in the 48 μm band is ~4″. As an spectrometer, SAFARI will offer a medium resolution mode (R~2000/4000 at 100/50 μm) and a faster low-resolution mode (R~200/400 at 100/50 μm). The latter one will be enough to efficiently detect the dust SED and the brightest cooling lines in very short times. Contrary to *Herschel* (very time-consuming and inefficient) this will allow us to map large areas of the sky in periodic intervals of time, opening new avenues for time-variability studies of protostars and protoplanetary disks in SFRs.

Transition from diffuse ISM clouds to GMCs:
SPICA will allow us to study the transition from diffuse clouds to GMCs where stars are form. By accessing the most important cooling lines of the ISM ([C II]158 μm in particular) and the dust SED, we will be able to constrain the gas thermodynamics at large-scales and relate it to the the formation of filaments and their fragmentation. Dense filaments in SFRs are embedded in a more diffuse and turbulent medium that seems to be driven on larger scales. As we have seen, these more quiescent and extended regions constitute the bulk of the GMCs mass and play a critical role in their evolution. In spite of their relevance, the interfaces between the SF cores and the environment are less characterised spectroscopically and thus remain poorly understood. Many questions still need to be answered. How are GMCs formed and destroyed?

Table 1. *Herschel* versus *SPICA* observations of YSOs in the far-IR.

Class 0 protostar	Serpens SMM1 at 200 pc *Herschel*/PACS	Serpens SMM1 at 2 kpc *SPICA*/SAFARI
Continuum at 100 μm	~250 Jy	~2.5 Jy
O I 63 μm (brightest line)	8E-15 W m^{-2}	8E-17 W m^{-2}
CO J=30-29 at 87.2 μm	7E-16 W m^{-2}	7E-18 W m^{-2}
Complete far-IR spectrum (R~2000 at 100 μm)	~3h (rms~5E-18 W m^{-2})	~4 min (rms~1E-18 W m^{-2})
10′×10′ fully sampled map (R~2000 at 100 μm)	~100 h for 1 line	<3 h* (full far-IR band)
10′×10′ fully sampled map (R~200 at 100 μm)	Not possible	<1.5 h* (full far-IR band)

*Assumes a pessimistic overhead of ~3 min between each consecutive FoV position.

How does SF affect their structure, evolution, and lifetime? (*feedback*). How does the environment determine the SF process? (*fragmentation*, *efficiency* ...)

While complete far-IR spectroscopic surveys of a handful of bright YSOs with *Herschel* provided the most complete information on the physical conditions and chemical content of individual sites of SF (hot cores, protostars, H II, etc.), they do not place the observations in the context of the large-scale emission (their environment). This has great relevance since it is the widespread gas and dust that set the initial conditions for SF. Contrary to *Herschel*, *SPICA*/SAFARI will map these faint extended regions both in the dust continuum and in bright cooling lines ([C II], [O I], [N II], ...), detecting individual objects and characterising their environment simultaneously. As noted earlier, ground-based submm telescopes such as ALMA cannot access the most important cooling lines of the warm/hot gas in YSOs. Nor can they observe the SED peak, which is essential to determine the dust temperature.

Spectral characterisation of protostars and planet-forming disks:
Mapping GMCs across the broad wavelength range of *SPICA*/SAFARI at multi-line mapping speeds orders of magnitude beyond the capabilities of *Herschel*, we will be able to completely sample a few appropriate SFRs for:
(a) short-lived first hydrostatic protostellar cores,
(b) protostars down to 0.01 M_{Sun} throughout the Class 0–I–II stages from 0.1–1 Myrs,
(c) planet-forming disks with a broad range of masses and evolutive stages.

The simultaneous observation of the complete SED, dust grain features and of a wealth of atomic fine structure, H_2O, high-J CO and HD lines will make *SAFARI a unique instrument to constrain the mass, the energy budget and the water content of hundreds of YSOs and disks*. Also very important, *SPICA*/MCS will be able to trace the hot gas and resolve the gas kinematics in many YSOs and disks, providing R~30,000 resolution at the wavelength of key H_2 rotational lines and of some mid-IR vibrational bands from organic molecules.

In conclusion, complementing JWST and ALMA observations, *SPICA* will allow us to understand the nature of these objects and to critically test star/planet formation and evolution theories.

3.2. Observing with *SPICA*/SAFARI

As an example of the powerful *SPICA*/SAFARI capabilities (Roelfsema et al. 2012), Table 1 shows one of the few protostars (nearby and bright) for which a complete *Herschel* spectrum exists (Goicoechea et al. 2012). In comparison with *Herschel* (a handful of bright individual objects and a few small maps of very bright lines), SAFARI will be able to carry-out unbiased spectral-mapping surveys of entire SFRs. For the first time in the critical far-IR domain, this will allow us to *characterise hundreds of protostars and planet-forming disks, together with their environment simultaneously*.

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