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FAR INFRARED ASTRONOMY AFTER SPICA

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ABSTRACT

This paper reviews the requirements for far-infrared astronomy in the period following the SPICA satellite in the late 2020's. We take a very long view of the state of FIR astronomy and what facilities will be required in a twenty year timeframe. We show that spatial resolution to match that of observatories operating in the optical and mid-infrared and the radio will be a necessity. Moreover this high spatial resolution must be combined with high spectral and photometric sensitivity to provide the data required to further our understanding of planetary formation mechanisms, the history of star formation through cosmic time and the feedback between active galactic nuclei and their host galaxies in controlling star formation. We review three possible conceptual mission scenarios and comment on the possibility of realising them in the coming deades.

Key words: Space; Missions; SPICA; Infrared

1. INTRODUCTION

Our view of the universe changed completely in the 1980's when the first infrared survey of the cosmos revealed that half of the non-cosmological background radiation arises at wavelengths in the far infrared, 30-300 μm band (FIR). In the three decades since the IRAS satellite (Neugebauer et al., 1984) made this discovery we have made much progress in understanding the processes that lead to FIR emission through missions such as AKARI (Murakami et al., 2007), culminating in the Herschel mission (Pilbratt et al., 2010) which completed operations in 2013. Together these facilities have allowed us to probe the fundamental processes of star formation, trace stellar and galaxy evolution and reveal the complex chemistry present in a large variety of astrophysical environments. Observations in the FIR trace the coldest regions of the Universe with gas and dust temperatures typically of 10's K. This very fact indicates immediately the difficult technical challenges involved in making these observations. The facilities have to be in space and both the collecting apertures and the instruments have to be cryogenically cooled. To date, some or all of this cooling has been achieved using expendable cryogens, making them complex pieces of engineering and limiting their operational lifetime. The startling progress in the 30 years between IRAS and Herschel shows what can be achieved and, with the knowledge gained from Herschel, we are in a good position to understand what is needed to continue that progress.

In this paper we discuss the requirements for future FIR facilities in the light of our current understanding and briefly touch on how the proposed SPICA mission (Swinyard et al., 2009) will fulfil some of those requirements. We illustrate the outstanding problems using a set of four test case observational problems and describe how these might be addressed by some mission concepts under active consideration by a number of groups. We conclude with some thoughts on the likelihood of a future FIR mission being constructed and the technical

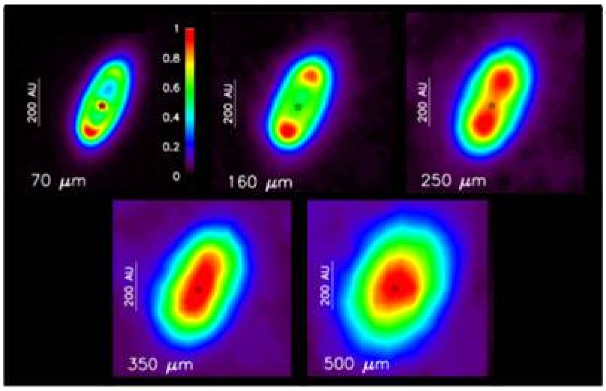

Figure 1. *Herschel* images of the dust ring around Formulhaut.

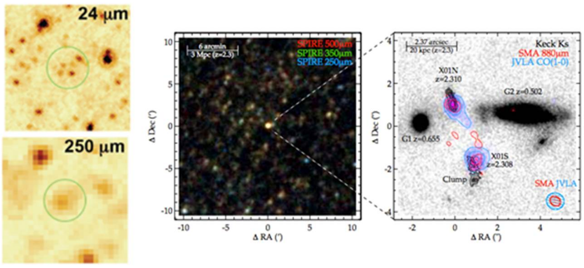

Figure 2. Two illustrations of confusion problems in identifying *Herschel* FIR galaxies.

roadmap that is needed to make it possible. In preparing this paper we have used the work of the FIRI consortium which proposed that a large FIR mission be considered for the next European Space Agency L-class mission (see Ivison et al. 2013).

2. SCIENTIFIC PERSPECTIVE - *HERSCHEL & SPICA*

Although it is rather too soon to give a full account of the historical impact of Herschel data on various topics, a number of tentative conclusions can already be drawn from the large number of papers published using those data. In the field of star formation large area photometric surveys (Molinari et al., 2010) have shown the almost ubiquitous nature of filamentary dusty structures associated with the onset of star formation. Somewhat unexpectedly continuing work in this area seems to show that these filaments have a fixed width of ~0.1 pc independently of the environment where they are discovered, indicating that turbulence within the ISM prints a size structure onto the dust and gas (Arzoumanian et al., 2011). The discovery of the presence of water in proto-planetary discs (Hogerheijde et al., 2011), whilst perhaps unsurprising, tells us that ultimately the chemistry of star formation leads to the chemistry of life itself. This is confirmed by the indicative result that the water in comets has the same isotopic make up as that in the Earth's oceans (Hartogh et al., 2011).

In the distant Universe, we been able to resolve the Cosmic FIR background (CIRB) into its constituent galaxies (e.g.Oliver et al. 2012) and confirmed that there were more of the Ultra Luminous IR galaxies (ULIRGs) in earlier epochs of the universe than observed in the local universe. With Herschel spectroscopy, only the local Universe could properly be observed although some higher redshift objects were detected (e.g. Ivison et al. 2010). Further analysis of the data combined with extensive ground based and mid infrared (from JWST) spectroscopic surveys will no doubt add to our knowledge. Even with SKA, ALMA and JWST we will not be able to access all the indicators of star formation over critical redshift ranges. In order to gain a full picture we need to access the far infrared from space and with sufficient sensitivity to see the normal objects rather than the biggest and brightest.

Similarly, whilst Herschel data, combined with those from ALMA and other ground based interferometers, are giving us a better understanding of star formation in our own galaxy, we have gained little information on the processes involved in planetary formation. Here both a lack of sufficiently sensitive spectrometers and a lack of spatial resolution has hampered attempts to really give a clear view of planetary formation from the thick, gas-rich proto-planetary disks phase to the dust and rubble of the final evolved systems. Only a few of the really nearby objects could be accessed and, although we have a more detailed picture of the processes in these objects, a comprehensive survey of many systems in a variety of stages of evolution and chemical and physical environments is necessary. This will only be possible with much greater spectral sensitivity combined, eventually, with much higher spatial resolution.

The basic issue of sensitivity will be addressed by the SPICA mission which will observe from at least 20 to 210 μm and will have a 3 m class mirror cooled to about 6 K. This mission envelope will provide an order of magnitude increase in sensitivity in the FIR compared to Herschel. The two areas where this capability will provide break though science are spectral surveys of the Herschel galaxies, revealing their nature and giving us a clear view of the mechanisms driving the star formation history of the Universe, and planetary formation, where we will obtain the first complete spectral view of oxygen and water chemistry in a large sample of proto-planetary disks. SPICA will also provide critical data for many other science themes where sensitivity has been the limiting factor notably the dust cycle in the ISM. SPICA, with much improved detectors and a cold solid dish is absolutely necessary in the next decade to continue the work of previous missions. However, one aspect will not change between Herschel and SPICA and that is the spatial resolution and really revolutionary progress in FIR observational astronomy will require a radical change in spatial resolution.

3. ILLUSTRATIVE CASES

It is impossible here to give a full justification of the case for high spatial resolution observations in the FIR (see Ivison et al. 2013 and references therein). We confine ourselves to four cases which highlight the need for high spatial resolution on spatial resolution scales of <1 arsec.

3.1. Planetary evolution

Figure 1 shows the Formulhaut debris disk as imaged by Herschel (Acke et al., 2012). This is one of a handful of debris disks that were resolved by current FIR observations and even here we see that at the longer wavelengths we lose image fidelity. Understanding the nature of debris disks such as this is important in understanding how the process of planetary formation plays out and gives us an insight into where the water, in the form of ice, is locked up in the final stages. Here the disk appears to be active in the sense that small body collisions are replenishing the dust in this relatively young system still undergoing rapid evolution. Many more of this type of object must be observed at this level of detail and over the full range from dense gas disks to fully formed planetary systems with Kuiper belt type dust disks. ALMA (in the sub-mm) and JWST (in the MIR) will add greatly to our knowledge, but they cannot access the crucial water emission features (whether solid or gaseous) or many of the solid state mineral features to characterise the dust. Only in the FIR does the full picture emerge and only with sub-arcsec imaging will we see a sufficient number of systems to form an unbiased view of planetary formation.

3.2. Massive Star Formation

The cartoon picture of star formation is well established from pre-stellar cores, through class 0 protostars to class III T-tauri type objects with large outflows. However, the conditions required for the formation and evolution of the most massive objects are not fully understood. In particular the energy balance between collapse and cooling through emission lines, particularly water, is critical to the end point of the process. Data from the HIFI instrument on Herschel have given some insight into the problem (Van der Tak et al., 2013) revealing multiple velocity components in the direction of a number of high mass proto-stellar objects which can partially be disentangled using the extremely high spectral resolution of HIFI. However, the true nature of the sources and how the various components interact with each other can only be fully understood by spatial separation. ALMA will be the facility of choice for continuing this work but can only access part of the spectrum and only high energy (i.e. hot) water lines. The cooler envelope and winds which control much of the energy balance can only be fully imaged from space.

3.3. AGN Feedback

It is now an undisputed observable fact that the cosmic star formation rate peaked at around z$\sim$2 and has dropped exponentially since then. It also seems to be the case that the star formation rate within the majority of galaxies is controlled by some complex interplay between the massive black hole at the centre of the galaxy and its host. However, how this feedback occurs and the detailed mechanisms that control star formation at the galactic and galaxy cluster scale are not at all understood. Recent observations give hints that there are large outflows of gas present in some sources. This indicates that some form of expulsion of the gas that might otherwise form stars occurs at a certain epoch in a galaxy's evolution; thus quenching star formation. One example of the detection of such an outflow in the FIR is given by Sturm et al. (2011) who have detected a large outflow of OH from the active galaxy Mrk 231. This outflow is seen in the absorption profile of the OH 79 μm line and is estimated to represent a mass loss of 1200 $M_\odot$ per year, an enormous rate. What is driving this phenomenon is not all clear and this question can only be properly resolved by probing directly into centre of the galaxy through high spatial resolution. Again ALMA will shed some light of the situation but only in low lying transitions of molecules such as CO. The bulk of the mass loss may still be missed and it is only in the FIR that molecules such as OH can be seen.

3.4. Galaxies at high redshift

Herschel has discovered tens of thousands of FIR and sub-mm bright galaxies (Oliver at al 2012). The identification of these sources and associating counterparts at other wavelengths presents a major difficulty, however,

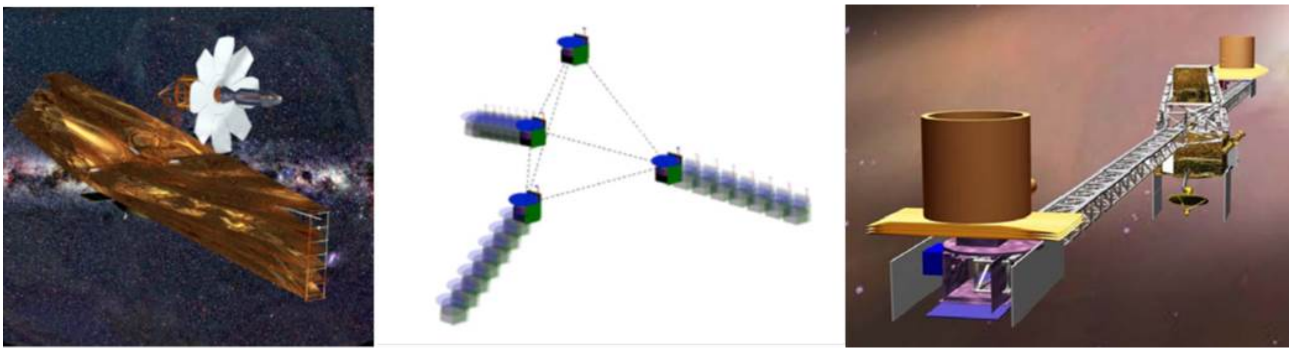

Figure 3. Examples of proposed future FIR space observatory concepts. From left to right (a) the SAFIR 10m cold dish concept (b) the heterodyne ESPRIT multispacecraft concept and (c) the SPIRIT structurally connected Michelson concept.

due the relatively large beam size of the Herschel telescope. Moreover, their redshift can only be confirmed using follow up spectroscopy from the ground (Casey et al., 2012) . This problem is especially acute when looking at the highest redshift objects which only appear at the longest wavelengths with the largest beam size. This is illustrated in the left hand panel of Figure 2 where multiple candidates are seen at 24 μm for a single source in the Herschel 250 μm image. Also shown in Figure 2 (right hand panel) is an example of a complex source seemingly undergoing a merger (Fu et al., 2013). Only with the spatial resolution offered by sub-mm and radio interferometers can we see its complex nature and even the presence of a bridge of material between the merging components.

4. FUTURE MISSION CONCEPTS

Having illustrated the case for high spatial resolution in the FIR we turn to how this might be achieved. The angular resolution of an optical system is governed by the maximum number of wavelengths across the primary aperture: effectively λ/D, where D the distance across the aperture. In solid aperture telescopes, such as Herschel, all spatial frequencies are measured simultaneously and an image is naturally formed with the highest spatial sampling given by λ/D and lowest by the field of view of the focal plane instrumentation. Other methods of achieving higher spatial resolution involve various implementations of sparse apertures which do not sample all spatial frequencies simultaneously and require the use of intermediate optics or phase sensitive detection to ensure the light from the separated apertures can be recombined in phase. There are three basic techniques that can be employed in the FIR which are illustrated by the three proposed space missions shown in Figure 3. In the first, which we might term a Fizeau interferometer, the light from an arrangement of apertures is brought together at a combined focal plane. The distributed aperture may be as shown in Figure 3a (Lester et al., 2005), may a be a ring like aperture (the TALC proposal, see Ivison et al. 2013) or could be arranged as separate telescopes with some form of phase correction system between them (Chung et al., 2004). The second possibility is essentially to place an ALMA or SMA type heterodyne interferometer in space. In the implementation shown in Figure 3b (ESPRIT see Helmich et al. 2005) four space craft are used each with an identical set of receivers phase locked to one of the spacecraft. The signals are correlated and different spatial frequencies are sampled by reconfiguring the spacecraft array in an exact analogy of the ground based systems. A third possibility is the more classical Michelson interferometer where the phase is directly measured between two apertures as the distance between them is varied. An implementation of this for the FIR has been extensively studied (Leisawitz et al. 2007, Figure 3b) which would use a double Fourier method to simultaneously measure both the spatial fringe visibilities and the spectral content of the signals. This system requires cold apertures and high sensitivity detector arrays similar to those developed for the SPICA mission.

The choice of system design depends to some extent on the scientific priorities. For instance: the narrow spectral window of a heterodyne system means that detecting and mapping broad band solid state is difficult; a sparse aperture Fizeau interferometer has a very narrow field of view meaning extended sources are difficult to image and both direct detection solutions have rather lower spectral resolution than required for many science topics. Technically all three systems are extremely challenging and costly. In principle a deployable system such as SAFIR will be proven with JWST, and most of the technology required for a heterodyne system has been demonstrated either on Herschel or in ground based systems. However, given the $8.5 billion cost of JWST, the prospect of a larger, colder version does not seem possible within any reasonable timescale. A heterodyne based system faces fewer direct technological challenges but, given the nature of the detection technique, requires rather more collecting area to provide the necessary sensitivity, immediately raising the cost. Here the major problems are phase locking between spacecraft, spacecraft station keeping and manoeuvring and the very large data rate between spacecraft and the ground needed for either on-board or ground based correlation. The Michelson solution perhaps has the greatest technical issues. A full scale system has not yet been demonstrated (although balloon borne systems are under construction); it relies for its sensitivity on cold mirrors which have to move along a deployed boom and the system has to maintain structural stability to very high levels whilst undertaking complex configuration changes and spacecraft manoeuvres. None of these aspects has been demonstrated on an operational space mission.

Whichever system is finally chosen the implementation will be expensive and will require co-operation between a number of space agencies. Such a large undertaking cannot be envisaged for least another twenty years. In the meantime the community, with the assistance of the space agencies, must look first to implementing SPICA and then to developing the necessary technology through smaller, more sceintifically focussed, facilties either on balloon platforms or in space.

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