Far InfraRed Discipline Working Group

(FIRDWG)

Astronomy in the Far Infrared, Submillimetre, or TeraHertz Wavebands

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Executive Summary

The Far Infrared Discipline Working Group (FIRDWG) has been given the task of investigating the future needs and opportunities for Canadian astronomers to participate in space missions with astronomical instruments working the far infrared (FIR, also called the submillimetre or terahertz) part of the electromagnetic spectrum. It is at these wavelengths where light is emitted by the processes that create most objects in the Universe. This is the part of the spectrum where the process of the formation of planets, stars, and galaxies "shines" the brightest.

The Earth's atmosphere is opaque to most FIR wavelengths and thus the study of these formation processes is very limited from the surface of the Earth. Canada has many astronomers working on the soon-to-be-launched Herschel Space Observatory that will be the first large FIR telescope in space. Herschel is expected to last between three and five years and will provide a wealth of scientific data to address many different problems in astronomy.

The FIRDWG's task is to plan for what the Canadian astronomical community will do in the far infrared after the Herschel mission is complete. The starting point for this planning is to look at what astronomer's scientific goals will be in five years. Since it is not known what will be learned with Herschel this exercise is not straight-forward and requires some "best-guesses". Another factor is the science that will be done with ALMA, a large millimeter interferometer under construction in Chile that will also have a tremendous capability at the longest wavelength end of the far infrared.

In this report we briefly list, and in a few cases summarize, some of the principle scientific topics that we expect will not be well understood, even after studies with Herschel and ALMA. These questions span scales from the relatively nearby edges of our own Solar System, to more distant star and planet forming regions in our Milky Way galaxy, to the most distant signs of the first galaxies forming when the Universe began.

We then look at what expertise and abilities we have within Canada to draw upon for building future far infrared instruments. Every year there are new ideas proposed for future far infrared missions. We summarize the current set of missions that could be useful for various parts of our science program. In order to participate in these missions Canada will need to contribute appropriate cutting-edge technology, most of which currently needs further development before being deployed in space. We provide a list of a number of technologies that Canada may be able to provide, if the development resources are available. Finally we provide a roadmap – a timeline of actions to be carried out over the next few years that will lead to Canadian participation in future far infrared missions in space.

Meetings of the FIRDWG

Feb 18-19, 2008	University of Waterloo
	19 participants (3 by videoconference from Victoria)
May 23, 2008	Canadian Astronomical Society Annual Meeting (Victoria)
	13 participants
Feb 18-19, 2009	University of Waterloo
	16 participants

Key Science Objectives

The team identified a wide variety of Science Objectives for future research in the far infrared. However it was felt that it was not possible to put these into a priority order at the current time given the imminent beginning of operations for Herschel and near-imminent beginning of ALMA, the two main instruments coming on-line shortly at these wavebands. These two instruments will be very powerful and are expected to make discoveries that will profoundly affect the science goals of the next generation of far infrared instruments.

However, the FIRDWG has attempted to determine the observations that will be of greatest interest to this next generation. Below we list a number of topics that we feel are likely to be objects of interest for a future mission in the FIR. We also describe questions that are likely to remain open even after observations with the new instruments. In addition to the topics described below, the next generation instruments will also provide exciting new information on: **planetary atmospheres; Kuiper belt objects and comets, asteroids; the black hole - galaxy connection; and HI recombination in the early Universe.**

Exo-planets, water and other ices

Water is a critical ingredient for life as we know it. While Herschel will observe gaseous water there is likely to be much water hidden from view as ice. It will be necessary to observe water ice in all environments, and explore its role on planetary formation and evolution, and the emergence of habitable planets.

Structure and chemistry of protostellar and protoplanetary disks; formation of solar systems

A critical stage in the collapse of a cloud of gas to form a young star involves the formation of a rotating gaseous disk. These disks both funnel material onto the surface of the star and drive large-scale outflows of material which carry away angular momentum and allow the collapse to proceed. These disks also provide the environment in which planets can form, either via local gravitational instabilities in the gaseous disk or by the slow agglomeration of dust grains to form small rocky objects. The bulk properties of the dust grains evolve during this process, causing changes in the far-infrared/submillimetre spectral energy distribution which can be measured if sufficient angular resolution is available to resolve the disk. In the nearest systems, angular resolutions of 0.1-1 arcseconds may be sufficient to resolve disks that are comparable in size to our own solar system.

The radial density and temperature gradient in these disks sets up a corresponding chemical gradient, one important feature of which is the “ice line”, the radius at which water vapour condenses to form icy mantles around the rocky grains. Beyond the ice line it is possible to form massive planets more quickly, while inside the ice line only limited quantities of rocky material are available. Forming planets can leave kinematical signatures in the disk itself, from radial gaps to spiral-shaped higher density arms. These features should be easiest to see in the far-infrared, where the emission from the dusty disk is at its peak.

Cloud cores and embedded stellar content

Stars form from high density gas cores embedded in a more diffuse gaseous environment. While recent observations have made a lot of progress in mapping out the earliest phases of star formation, obtaining sufficient sensitivity and angular resolution still provides significant constraints. This is especially true for understanding the formation of the most massive stars (10-100 times the mass of our Sun). These relatively rare objects are typically found at larger distances from the Sun and also form preferentially in groups and clusters. Thus, high resolution is critical to separating individual massive stars in formation from their surrounding environment.

Far-infrared/submillimetre wavelengths probe the peak of the spectral energy distribution of dust emission in star forming regions. This makes far-infrared maps exquisitely sensitive probes of the early phases of star formation. Far-infrared maps with 1 arcsecond resolution would allow astronomers to distinguish all but the closest multiple star systems in nearby regions of massive star formation and remove an important ambiguity to our understanding of how massive stars form.

HD observations for total mass

The HD molecule is a good tracer for gas mass in most environments where H_2 dominates the mass. HD is found in an abundance of slightly greater than 10^{-5} of the molecular hydrogen, similar to the usual molecular tracer CO. HD is also a strongly emitting molecule and potentially very bright. However it's lowest rotational transition (the best transition for mass measurements) is at a wavelength of 112 microns, in the centre of the FIR band where the Earth's atmosphere is opaque.

One reason for the utility of HD is that it is not strongly affected by temperature (a large fraction of the molecules are in the lowest states at the usual interstellar medium temperatures), density (it is optically thin), or chemical effects (very little chemical fractionation occurs, unlike in other deuterated molecules). These properties make HD one of the best molecular tracers of mass. The other alternative for tracing mass is using dust. However the use of dust for mass (column density) measurement is dependent on the physical characteristics of the dust. In the past it has been assumed that all dust is the same, or at least very similar, but this assumption has been challenged a number of times in the past few years. Also, it is certain that in dense circumstellar disks, where planets are forming, the dust must change substantially as the solid particles grow from sub-micron size to the size of the Earth! In such environments dust is a very uncertain mass tracer.

ALMA will be unable to observe at the frequency of the HD line and Herschel will have neither the spatial resolution nor the velocity (frequency) resolution necessary for most objects of interest. However the PACS instrument of Herschel is capable of detecting the HD line. The results from those observations, and in particular their limitations, will be important for determining instrument characteristics for a future HD mission.

Polarization in many environments as a probe of magnetic field morphology

Magnetic fields provide an important source of support against gravitational collapse in the dense clouds and cores where stars form. Magnetic fields are also thought to be intimately related to the large-scale supersonic turbulence which is seen in these regions.However, relatively little is known about the morphology and strength of magnetic fields in star forming regions. The strength and morphology of magnetic fields is a key prediction of star formation theories.

Far-infrared polarization observations would have a unique sensitivity to magnetic fields by working at wavelengths near the peak of the emission spectrum from dust grains. Observing from space would have the additional advantage that magnetic field morphologies could be mapped over a much broader range of angular scales than comparable observations from the ground at millimetre wavelengths. This is because ground-based observations must "chop" (i.e. measure the difference between two positions on the sky) in order to remove the time-variable effects of the Earth's atmosphere. Observations of polarized emission over a range of wavelengths can also provide constraints on the physical properties of the dust grains producing the polarized emission; it is difficult to get a large enough range of wavelengths with ground-based data alone.

Local galaxies

Nearby galaxies allow us both to place our own Galaxy in the broader context of galaxy properties and evolution and also to study environments that are substantially different from those found in our own galaxy, including regions with extremely high star formation rates or low abundances of heavy elements. Observations at far-infrared/submililmetre wavelengths for all but the nearest galaxies are hampered by the limited resolution and sensitivity of previous instruments. While Herschel will be a large step forward in this regard, its angular resolution corresponds to scales of many thousands of light years in the vast majority of nearby galaxies. Instruments with higher angular resolution (approaching 1 arcsecond) would allow astronomers to study the gas and dust and the stars that form from them on spatial scales of less than a thousand light years in galaxies out to distances of 500 million light years. This volume of space contains numerous examples of unusual galaxies, such as galaxies undergoing intense bursts of star formation and galaxies containing active nuclei powered by a central massive black hole. With the capability to study many galaxies of a given class, rather than just the single nearest object, we will place our understanding of galactic evolution on a much firmer footing.

Galaxy Formation and Evolution: Resolving the Cosmic Infrared Background and the History of Cosmic Star Formation

In spite of the many recent observational advances in this area, there remains a glaring disconnect between standard cosmological theories of large scale structure formation and our understanding of structure growth on galaxy scales. Indeed the relatively simple physics of the now standard precision cosmological model (Lambda-CDM) cannot predict the complex physics of regions of the universe dominated by baryonic matter. Current mysteries include the cause of the 'downsizing effect' wherein the dominant sites of star formation in the universe migrate from high-mass to low-mass systems with time, in direct conflict with the predictions of semi-analytic models. It is also clear that the local environment of galaxies plays an important role their evolution in ways we do not understand, and that there is a tight connection of uncertain nature between the growth of the supermassive black holes in the centers of all massive galaxies and their stellar components.

It has long been recognized that roughly half of the energy radiated by all objects integrated over time and space, i.e. the so-called extragalactic background light, is radiated at infrared wavelengths. This radiation is primarily due to the re-emission of optical and ultraviolet light by dust grains (thermally and non-thermally) which seem to accompany all processes of formation in the universe. Thus, any study of the formation of galaxies necessitates deep infrared observations as many of the relevant processes cannot be detected at shorter wavelengths.

We have made great in-roads in this area through the current generation of infrared facilities such as SCUBA and Spitzer, which have resolved a substantial fraction of the infrared background into individual objects and has allowed studies of the most luminous phases of galaxy formation. These facilities have however suffered from large beams and thus high confusion when imaging the high-redshift universe, and limited spectral abilities. ALMA and Herschel will be great steps forward but cannot provide all of the answers. Herschel will still suffer from high enough confusion that extragalactic science will be limited, in particular at its longer wavelengths while ALMA, though powerful, will not have the wide field-of-view required for efficient coverage of large survey areas and is focused on frequencies below 950 GHz.

A powerful mid-far-infrared mission will fill an important niche in extragalactic astronomy. For example, a sensitive wide field mission with spectroscopic capabilities could compensate for spatial confusion through the addition of spectroscopic information (essentially the third spatial direction). The mid and far-infrared region will probe hotter components of galaxies than ALMA (which samples cold processes), such as thermally emitting hot dust surrounding AGN and star-forming (HII) regions. Many important ionic transition lines, key for studying the physics of star formation and AGN activity are found short ward of ALMA's longest wavelength, as are the polycyclic aromatic hydrocarbon features, which are sensitive probes of the energetics of a galaxy. Given that the outstanding questions of galaxy formation focus on the progression and nature of star formation, the feedback between AGN and star formation, and the physics which drives this activity, sensitive probes of these processes are crucial.

Canadian Expertise

The FIRDWG attempted to identify all of the resources available in Canada for a future FIR mission. However it was impossible to identify all of the industrial resources… there were too many!

University teams(Professor leading the team):

- UBC (Halpern) – electronics for SCUBA-2 and numerous cosmology missions/instruments
- UBC (Scott) – Data Reduction Software and analysis algorithm development"
- Lethbridge (Naylor) – FTS and related hardware for JCMT, SCUBA-2, SPIRE testbed, data processing software
- U.Western Ontario (Houde) – polarimeters
- U. Waterloo (Kycia) – large scale screening of SQUID devices, cryogenics, now building TES bolometers,
- U.Waterloo (Fich) – FIR instrumentation specification/design & project management
- U. Toronto (Netterfield) – balloon-borne FIR instrumentation
- U. Montreal (Bastien) – polarimeters
- McGill (Dodds) – bolometers
- also Calgary ISIS, Lyertech (FPGAs), ALMA band 3, NRC/HIA and Candian corporate partners
- Also teams from MOST, UVIT, JWST, NEARSAT (e.g. at York)

Government:

- Herzberg Institute for Astrophysics at NRC
    - Large resource – many scientists and engineers and technicians
    - Extensive experience with JCMT and ALMA (and DRAO, SKA, …)
    - Extensive space experience with HST, JWST, and a variety of UV missions (plus CFHT, Gemini, TMT, …..)

Industrial teams:

- Com Dev International has strong background in electronics and optics in space
- MPB Communications – miniature IR spectrometers, fibre-optic sensors (e.g. on ESA Proba-2), smart materials (ESA radiators) (design work on HIFI LOSU)
- ABB Bomem – FT-IR
- Blue Sky Spectroscopy – THz FTS and Herschel SPIRE data processing software

… and too many others to list here, complete satellite manufacturers…

Opportunities

The FIRDWG attempted to list all of the opportunities that members had heard about in the past few years.

SPICA – The JAXA-led SPICA mission is proposed to carry 3 instruments: a Mid-IR Coronograph, a Mid-IR Imaging Spectrometer, and a Far-IR Imaging Spectrometer. On the ESA side, a participation to SPICA has been proposed to the Science Program in the context of the first Call for Missions of the Cosmic Vision 2015-2025 program. The foreseen ESA participation consists in the cryogenic telescope assembly, and in a contribution to the operations in the form of a European SPICA ground segment. The Assessment Studies for the proposals selected in the context of the first Call for Missions of the Cosmic Vision 2015-2025 plan are planned to last until mid 2009, and will be subject to a competitive down-selection in late 2009. The mission concepts which will pass the selection process in late 2009 will be then subject to Definition Studies in 2010-2011, and be subject to a competitive selection phase in late 2011, leading to the final choice of the missions which will fly in a 2017-2018 time-frame.

Following the recommendation of the SSAC, and consistently with the framework for the first cycle of the Cosmic Vision 2015-2025 plan, an Assessment study for the ESA contribution to SPICA has been started, and it will last until mid-2009. In parallel with the proposal for an ESA contribution to SPICA, interest has been expressed for the provision of an European SPICA Instrument (ESI, a Far-IR Imaging Spectrometer), to be provided under a funding arrangement based on dedicated contributions from the ESA member states, with the ESA Science Program providing the systems engineering and the management of the instrument, as well as a single interface to JAXA. Contributions to this instrument are also proposed to be funded by the Canadian CSA, by NASA

SPICA status within JAXA: Following a successful mission definition review (MDR) in March 2008, the SPICA project team received funding through the System Definition review (SDR) to be held in late 2010 and Project approval review in June 2011.

Canada is contributing to the SPICA SAFARI instrument through evaluating the performance of proposed detectors coupled to an FTS and through the development of a SAFARI instrument simulator.

FIRI – a large FIR interferometer proposed by diverse European team. A proposal to FIRI development was submitted to ESA under the Cosmic Vision process but the proposal was not accepted for major funding for development. However the European team will continue the development of this project, primarily using funds from national agencies rather than from ESA. This team has been active as a team since 2002. The FIRI team is still debating the issues of direct detection vs heterodyne interferometers.

SPIRIT – a US proposed FIR mission with a small number of large telescopes and a beam combiner to allow direct detection interferometry.

Millimetron – a Russian mission to place a very large single aperture millimeter-wave telescope in orbit.

SAFIR – a US proposed mission with a 10 meter cooled telescope. This would be a very challenging mission and is unlikely to be launched before 2030. However it would be a very powerful instrument!

Interferometer on moon – there are no teams funded to work on this project but this instrument has been discussed in a number of venues over the past few years.

C+ and HD interferometers – specialized missions with (probably) two small antenna acting together as a one-baseline interferometer.

Balloon-borne interferometers – These might be the platform for the C+ and HD interferometers with the two antennae hanging below the balloon, one of the antennae would be able to move up and down, hanging below the other antenna, and thus a variable baseline (in the z-direction) would be effected.

Technology

Single antenna *vs*
heterodyne interferometer *vs*
direct detection interferometer

The FIRDWG discussed these related questions: (1) should the next FIR mission be a single antenna mission, like Herschel, or an interferometer; and (2) should the first FIR interferometer mission be a direct detection or heterodyne instrument? The answers to these questions depends on both the science questions to be addressed (e.g. as listed above) and on the technology available.

A single antenna mission has two major instrumental parameters: the size and the temperature of the dish. SPICA will improve upon Herschel by using a much colder antenna. This will improve the sensitivity for all instruments but will offer the biggest improvement to direct detector instruments. Thus the biggest scientific gains are for projects requiring photometry or low-to-medium spectral resolution. To gain in sensitivity and spatial resolution will require significantly larger antenna. It is unlikely that such large antennas can be made in one piece and still fit within a launch vehicle; Large antenna will require deployment in space (e.g. unfolding antenna mirror panels) which is a great deal more expensive. The JWST is an example of such a deployable mirror.

The two types of interferometers both offer a large improvement in spatial resolution over single antenna. Direct detection interferometers will consist of two or three antennae that reflect the incident light into a beam combiner. Heterodyne interferometers can consist of a large number of antennae but must share a common Local Oscillator (LO) signal. Both methods have a challenging requirement to measurement and control of distances between optical elements (the antennae). For both types of interferometers it is possible to have free-flying antennae (ie separate satellites) or connected antennae (either through tethers or on structural elements). The trade-offs inherent in these methods will require a significant amount of analysis. At the moment the direct detection interferometer teams are “leaning towards” antennae on a single structural element while the heterodyne teams favour free-flying antennae.

The instrumentation for the direct detector missions have one major challenge, whether single antenna or interferometer: the detectors. The current generation of detectors (e.g. TES detectors as in SCUBA-2) are two to three orders of magnitude too noisy for these missions. There are a number of promising technologies suggested by recent research teams but all are far from being well understood. Heterodyne detectors are only slightly better off: the low noise SIS receivers used at lower frequencies have high frequency cutoffs of approximately 1.2 THz and the Hot Electron Bolometers used up to 2 THz in Herschel are much more noisy than SIS technology. Heterodyne systems suffer from another problem: producing a tunable LO signal at THz frequencies is difficult.

Much more could be written about the technical challenges for all of these kinds of missions. For the moment we leave this with the note: any future FIR mission has significant technology challenges that need to be faced, and solved, before significant work on the mission itself can go ahead.

In a brainstorming session at the final DWG workshop we attempted to identify as many of these challenges as possible. Below is the list of these, with some comments added for a few items:

- 350 micron interferometry test bed
- robotic booms
- pointing sensors
- metrology
- formation flying
- instrument control software
- Double Fourier (spatial/spectral) analysis software
- THz heterodyne test bed
- Direct detection systems – detectors, bolometers (TES, with SQUID multiplexors, as in the SCUBA-2 camera at the JCMT)
    - MKID (Microwave Kinetic Inductance Detector) is a new detector design based upon a superconducting resonance circuit that can be used in combination with a suitable radiation absorber or antenna to detect radiation from the sub-mm range (at a frequency of 100~GHz, and wavelengths around 1 mm) to the X ray (at photon energies of several keV). The main advantage of the MKID principle is that it is very easy to do frequency division multiplexing. This will enable the design and realization of large arrays.
- Heterodyne detectors
- Local oscillator systems
- Focal plane optics

Road-map

Near-Term (5 years):

1. SPICA (earliest launch date 2017)
2. watch/monitor/'continue participation in' Herschel science results, and also technology performance (2011)
3. technology development (detectors, spaced-based interferometery)
4. Small CDN project - balloon or microsat –
    a. a dedicated line (C+, HD?)
    b. all-sky survey, polarization
    c. balloon borne SPICA
    d. balloon borne interferometer

Medium Term (5 to 15 years):

1. watch/monitor/'continue participate in' ALMA science results (2013)
2. technology development (detectors, spaced-based interferometery)
3. FIRI
    a. Depends on design, especially baseline
4. SAFIR

Long Term

1. Space interferometers with focal plane arrays
2. Lunar-based astronomy

Recommendations

1. The SPICA mission is a very attractive option for a mission to be launched within the next 10 years. There are natural opportunities for Canadian involvement through the SAFARI instrument, especially given our expertise in FTS technology and software from Herschel. We should explore options to join SPICA/SAFARI by providing software as well as personnel for the ICC and EGSE.

2. Balloon-borne experiments provide an attractive possibility to test some of the components involved in a far-infrared interferometer as well as new detectors for filled-aperture missions. They could be particularly useful for testing the performance of direct detection interferometers (for comparison with heterodyne systems). Canada should continue to be involved in balloon-borne experiments in this wavelength range.

3. There are a number of exciting new missions that are in the earliest planning stages but for which launch is more htan 10 years away. We should continue to monitor international proposals for new missions and help to develop the science and technical cases where possible, so as to be involved in the definition of the mission parameters from the beginning to ensure maximum scientific and technical return to Canada.

4. We should develop technologies that will enable Canada to participate in the mission(s) that will enable us to meet our scientific goals.

5. We should monitor and encourage participation by Canadian scientists in the scientific exploitation of facilities about to come into operation, especially the Herschel Space Observatory.

Appendix A

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