VOLUME II

Canadian participation in the European Instrument (ESI) on the JAXA *SPICA* mission*.*

Background

The mid to far-infrared region (~ 5-200 μm) of the electromagnetic spectrum is an important window for studying the physical and chemical processes taking place in a wide range of astronomical sources. Broadband access to the far-infrared is possible only from stratospheric and satellite platforms due to absorption by the Earth's atmosphere. Several highly successful space observatories have been flown over the years to exploit the spectroscopic opportunities in this waveband, including *ISO*, *IRTS*, and now *Spitzer*. To date, infrared space missions have all had cryogenically cooled apertures of less than 1 metre, and so have been limited in terms of collecting area, angular resolution, and sensitivity. While the spectroscopic instruments on board *ISO*, for example, have shown the power of far-infrared spectroscopy in studying the physics and chemistry of the interstellar medium, *ISO*'s spectroscopic studies were restricted to the study of the local universe due to its limited sensitivity.

Planned missions

The JAXA mission *AKARI* (*Astro-F*), was launched on 22 February 2006 and is conducting an all sky survey at wavelengths of 12, 20, 60, 170 μm at angular resolutions of 30 – 50" (determined by the small 0.69 m telescope), and sensitivities 10 - 100 times better than the IRAS survey, and its survey spectrometer covers the wavelength range 50 – 200 μm. ESA's *Herschel Space Observatory*, to be launched in 2008, will have a larger 3.5 m aperture, passively cooled to ~80 K, leading to a major advance in spatial resolution and sensitivity. However, its warm aperture will limit its ultimate sensitivity for photon-starved spectroscopy, and it will not cover wavelengths below 60 μm. The *JWST* will be launched ~2012 and will have the equivalent of a 5.8 m aperture but will only cover the wavelength range from 1 to 27 μm, thus missing the peak of the cosmic infrared background emission and all of the most important "cooling" lines in the interstellar medium of our own and other galaxies. In addition, the *JWST* will be limited at the long wavelength range by its relatively warm telescope.

SPace Infrared telescope for Cosmology and Astrophysics: *SPICA*

While *AKARI* and *Herschel* are pioneering missions, they are not able to exploit the sensitivities achieved by the current state-of-the-art far-infrared detectors. To address this sensitivity gap the Japanese space agency (JAXA) has proposed the *SPICA* mission (launch ~ 2017). *SPICA* will have the same sized aperture as *Herschel*, but the telescope will be cooled to liquid helium temperature, and the scientific instruments operate over the wavelength range of 5 - 200 μm. With its cooled, optical quality, 3.5 m diameter mirror, *SPICA* will combine the advantages of a low thermal background with increased collecting area and superior angular resolution to achieve sensitivities **20 to 1000** times better than *Spitzer* and *Herschel* depending on the detector technology available. *SPICA* will also match the sensitivity of the *JWST* at around 20 μm due to its lower temperature telescope, albeit with slightly lower angular resolution. The *SPICA* mission, therefore, represents a major increase in sensitivity in the mid- to far-infrared, which will open up a previously unexplored region of parameter space.

European Instrument for SPICA (ESI)
In recognition of European expertise in infrared astronomy, the JAXA, under the leadership of Prof. T. Nakagawa, has invited a consortium of European scientists, many of whom have previously worked on the *ISO* and *Herschel* missions, under the leadership of Dr B. Swinyard, to provide a European Instrument (ESI) for *SPICA*. In order to exploit the capabilities of the *SPICA* mission an imaging Fourier Transform Spectrometer (iFTS), of design similar to that of the SPIRE instrument on *Herschel*, has been proposed for the ESI. Given Canada's proven track record in the field of far-infrared Fourier spectroscopy, and the well established collaboration with our European colleagues through the *Herschel*-SPIRE project, the opportunity has presented itself to participate in this exciting mission through joining the ESI effort.

Canadian contributions

In contrast to Canada's involvement with *Herschel*-SPIRE, in which it joined a project at a stage when the instrument design was already frozen, an early involvement in *SPICA*/ESI will allow for Canadian input to the instrument design.

As the Canadian Co-I on the *Herschel*-SPIRE mission and the PI on the FTS-2 spectrometer being developed for use with the submillimetre camera, SCUBA-2, for use at the JCMT, Dr Naylor's team has over 50 years of experience in the design and use of far-infrared astronomical Fourier spectrometers. The contributions of his team are highly regarded within the European SPIRE consortium. Since the ESI consortium consists of many of the scientists who built the scientific payload instruments for *Herschel*, and further that the baseline design for ESI is an imaging Fourier transform spectrometer, Dr Naylor's group is ideally positioned to lead a Canadian involvement in this project.

The primary objective of the study phase will be to compare and contrast the performance of the different detector technologies when coupled to an iFTS, from both experimental and theoretical perspectives. While an imaging Fourier transform spectrometer has been selected as the baseline design for ESI, the choice of detectors is still open. At least two detector technologies are being seriously considered: state-of-the-art transition edge sensors (TES: similar to those used in SCUBA-2) and the latest generation of photoconductors. Each has its own set of unique problems when coupled to an iFTS.

While it is difficult to simulate the low temperature environment of the entire ESI instrument in the laboratory, measurements of the response of the detectors to rapid changes in detected energy (for example, by using an external warm FTS with cryogenic neutral density filters, or a co-located low dosage radioactive source within the detector dewar) will be analyzed to determine their impact on the retrieved spectrum. The experimental aspect of this work will be conducted in Dr Naylor's well-found laboratory, which houses 4 Fourier spectrometers covering the entire infrared spectrum from 1 – 1000 μm.

The theoretical aspect of this work will extend upon the Simulator for the Herschel Imaging Fourier Transform Spectrometer (SHIFTS) which was written in IDL to model the performance of the SPIRE spectrometer. Synthetic data products generated by SHIFTS are currently being employed by the SPIRE instrument teams to analyze results from the SPIRE instrument test campaigns of the flight model instrument. SHIFTS has been shown to generate realistic data products for the SPIRE imaging spectrometer using existing subsystem qualification data (Lindner, Naylor & Swinyard 2006). SHIFTS' modular design lends itself to be extended to model the performance of ESI taking the physical conditions of the SPICA telescope and the ESI wavelength range into account; this work will involve modifying already existing and adding new components to the simulator.

Another important, project wide task to be completed during the study phase include the writing of a science implementation plan, which will define the scientific constitution including data rights. Dr Naylor and his science team will work closely with European and Japanese colleagues to ensure that Canadian astronomers receive adequate scientific compensation for a contribution to the project. Initial discussions in this regard, which are based on the *Herschel*-SPIRE experience, have been very positive.

Finally, it will be important to champion the project at appropriate venues (conferences, workshops etc) and make Canadian astronomers aware of the potential of *SPICA*-ESI mission. While it is always challenging to maintain enthusiasm for a mission with a launch date of ~2017, the task will be somewhat easier given the impending launch of *Herschel*, a mission which will pave the way for *SPICA*.

In summary, the proposal team is in an excellent position to make a critical contribution to the ESI study phase in terms of instrument performance analysis; design improvements; laboratory testing of instrument concepts and analysis software. The modest funding available for the study phase will be leveraged against other funding sources (NSERC, CFI, ASRIP, CSA) to accomplish this goal.

Scientific and Industrial benefits to Canada

While at this stage it is too early to define in detail the return to Canadian astronomy, based on previous collaborations between JAXA and ESA it is expected that data rights will be generous. Indeed, as mentioned above one component of the initial study phase will be the development of a Science Implementation Plan (SIP) in conjunction with the JAXA, which will define the scientific constitution including data rights.

By joining the ESI effort Canadian scientists will not only have access to the guaranteed time allotted to the ESI instrument team (the exact amount is TBD and will be determined during the development of the SIP), but they will also be ideally positioned to exploit the open time component of this observatory class space mission. History has shown that Canadian scientists hit far above their weight class when it comes to competing for observing time on international space astronomy missions.

From the rather small Canadian involvement in ESA's pioneering *Infrared Space Observatory* mission, to the significant contributions to the Herschel and Planck missions, in less than a decade Canada has developed an international reputation in the field of far-infrared space astronomy. In order to maintain this momentum it is important for Canada to participate in the next generation of far-infrared space astronomy missions. The invitation by the ESI team to join their efforts is a direct reflection of the high regard in which Canadian expertise if held.

The role for Canadian industry in this mission is TBD, but it is fair to say that there exist in Canada several companies with highly relevant space related experience who could benefit from participating in this mission via CSA, ESA or JAXA contracts.

Fit with the CSA program, strategy and Canadian science priorities
In November 2006 the CSA sponsored a space astronomy workshop (CSAW), a brainstorming session in which scientists were asked to think about the big questions in astronomy, what type of space mission could address them, and what role Canada might play in such a mission, from leading a mission to being a significant partner in one. SPICA was presented at that meeting as a mission in which Canada could become involved as a minor partner. Its broad spectral coverage in the far-infrared and vastly superior sensitivity, to existing or planned missions, coupled with its complementary fit with the JWST and observatory class nature were recognized as having broad appeal.

The NRC-NSERC sponsored long range plan for astronomy (LRP - 1999) noted that "the coming two decades will see the development of new types of observatories both on the ground and in space that will catapult to new levels, our knowledge of everything from the formation of planetary systems, stars, and galaxies, to the structure of the universe itself. Our investment in this truly exciting age of cosmic exploration will have benefits for many areas of fundamental astronomical and scientific research, public education and culture, and technological and industrial development."

The recommendations of the Long Range Planning Panel represent the consensus of the entire Canadian astronomical community for its priorities in astronomy in the coming decades. The very complexity of the origin and evolution of structures in the universe implies that no single telescope can be the complete tool with which to address these problems The unified vision of astronomy and astrophysics emphasizes the need for a complementary set of ground and space-based observatories. This vision includes participation in the emerging world observatories, as well as international and national observatories; growth in the research capabilities of our leading institutes and universities; extensive investment in the training and support of the most talented young scientists; the development of important public and educational outreach programs; the inspiration of the younger generation to enter technical fields; and the stimulation and participation of many Canadian high-technology firms and industries.

With the release of the ESA Cosmic Vision AO the opportunity has presented itself for Canada to become a partner in the SPICA mission through joining the ESI consortium. This invitation builds on the highly regarded Canadian contributions to the Herschel mission and is in line with the Canadian science priorities as expressed in the LRP and the thrust of the CSA space astronomy program.

Management capabilities of the team

Each member of the science team has extensive experience in multinational collaborations and each recognizes the important role of management to achieve the project goals. Communication is the key to successful collaborations and the excellent working relationships with our European colleagues developed during the course of the Herschel/SPIRE project (many of whom are now working on ESI) will prove invaluable in this regard.

Dr Naylor is the Canadian co-I on the Herschel SPIRE mission, the PI on the Fourier spectrometer under construction for use with the SCUBA-2 camera, and the PI on the IRMA project (his annual research funding in support of these activities exceeds 1M$ pa). A local project manager is assigned to each of these projects to coordinate the technical team and handle the external interfaces. With the modest funding available in the initial study phase of this proposal, the work to be conducted will be managed by Dr Naylor in a supervisory relationship with the post-doctoral fellow to be hired. Should the project be selected for further study and ultimately launch, the budget includes continuing funding for a project manager.

Technical feasibility and risks

The proposed work during the initial study phase focuses on the testing of state-of-the-art detectors under low background conditions. While this work is challenging, the infrastructure required exists within Dr Naylor's Astronomical Instrumentation Group. Single pixel detectors will be provided by the ESI team. The detectors will be installed in test cryostats and coupled to a Fourier spectrometer for analysis.

The proposed work lies well within the skill set of the team. Should delays be experienced with the delivery of detectors, work will focus on the development of the software-based model, SHIFTS, to simulate the response of the detectors being considered for ESI: TES and photoconductors.

As part of their contributions to the SCUBA-2 project Dr Naylor's team will shortly integrate a Fourier spectrometer with SCUBA-2 and gain invaluable experience in the use of TES detectors in conjunction with an interferometer. There are significant synergies between the Herschel/SPIRE, SCUBA-2/FTS-2 and SPICA/ESI project because of the very similar optical design. Access to knowledgeable collaborators in these various projects will further reduce the technical risk associated with the proposed investigations.

Canadian science team

David Naylor, Professor of Physics and Board of Governors Research Chair, University of Lethbridge

Dr Naylor's research program is centered on a laboratory for experimental astrophysics. Over the last two decades he has established an international reputation for this work at the UL. The primary goal of this laboratory is the development and use of sophisticated far-infrared and submillimetre spectrometers and radiometers in a range of astronomical projects. While historically this has been somewhat of a niche research area, these skills are now proving to be in great demand as both the Herschel/SPIRE and SCUBA-2 projects target the submm spectral region, one of the last explored regions of the electromagnetic spectrum.

Dr Naylor is the Canadian co-investigator on ESA's Herschel/SPIRE mission, the PI for the imaging spectrometer under development for use with SCUBA-2 and the PI for the infrared radiometer, IRMA, developed for phase correction and site testing applications. He has served on several national and international scientific committees and has extensive reviewing experience. His research funding has included support from: NSERC, CFI, ASRIP, NRC, NASA, ESA, CSA, QMW, NATO. Since 1981 over 75 students have worked in his laboratories, all, without exception, have gone on to graduate studies (most with scholarships) or found full time employment after graduation.

James Di Francesco Astronomer, Millimetre Astronomy Group, National Research Council Canada, Herzberg Institute of Astrophysics; Associate Professor of Physics and Astronomy, University of Victoria; Associate Professor of Physics and Astronomy, University of Calgary

Dr Di Francesco's research has focused on the evolution of the youngest stars, to understand better our own origins in the Solar System. To explore this evolution requires observations at both near-infrared to millimetre wavelengths, since it is in this regime where faint emission from the cold gas and dust involved in star formation is seen, from the dense cores out of which stars form to the icy debris left over from the formation of their planetary systems. Such observations are difficult from Earth, due to the low transparency of the atmosphere at these wavelengths. While initial studies of debris disks and circumprotostellar envelopes were performed using the NASA Kuiper Airborne Observatory, which flew above most of the absorbing components, at these wavelengths space-based observatories are preferred.

Dr Di Francesco is a Canadian Associate Scientist on the Herschel SPIRE consortium and has played a key role in defining the circumprotostellar envelopes and debris disks observing program that will be conducted with Herschel as part of the Guaranteed Time Key Projects.

SPICA represents an exciting step forward in understanding the far-infrared Universe as a result of its vast increase in sensitivity compared to *Herschel*. These sensitivities will allow large-sample spectroscopic studies that will be impossible with *Herschel* given its limited lifetime. Most importantly, SPICA will allow, for the first time, broad probes of the evolution of gas and dust in the inner regions of circumstellar disks, i.e., at locations analogous to where the Earth likely formed. SPICA will observe numerous important cooling lines from molecules such as water and oxygen that are excited at the densities and temperatures of inner disks but which are inaccessible from the Earth's surface. SPICA will also reveal spectral energy distributions across far-infrared wavelengths that yield information about the disk dust and their icy mantles from their slopes and from wide absorption features within the continuum emission.

SPICA not only represents the most logical extension to the pioneering observations of ISO and Herschel, but it also complements the longer wavelength yet higher spatial resolution observations that will be produced by ALMA. Simply put, SPICA would significantly extend my research into new regimes. It is Canada's best near-term opportunity to explore the origins of the Earth and the Solar System.

Mark Halpern Professor, Department of Physics and Astronomy, UBC

Mark Halpern has a long history of performing cosmological measurements and building the instruments to do so starting with the first submillimetre measurements of the dipole moment of the cosmic background radiation in the 1980's. His measurement of the spectrum of the CMB with a cryogenic fourier transform spectrometer on a sounding rocket provided the most accurate determination of the temperature of the CMB even after COBE, and two of his papers resulting from WMAP measurements of the primordial anisotropy of the CMB have been rated by ISI as the two most influential papers in all of science published in the past 5 years. His current research includes BLAST, a balloon borne telescope to survey star formation at high redshift which just completed a very succesful eleven day flight. He is also actively involved in the Atacama Cosmology Telescope, designed to study clusters at the moment of first formation via their effect on the CMB, which had first light in June 2007. He is a member of the Herwchel/SPIRE team studying the high redshift distribution of galaxies.

Recently Halpern's laboratory at UBC have become the world leaders in readout electronics for the large format superconducting bolometer arrays which are revolutionizing submillimetre astronomy. These electronics, initially developed for SCUBA2, are in use on the ground based instruments ACT, CLOVER and BICEP and the airborne and near space experiments Spider and a NASA Goddard-led camera for Sofia. He and co-workers are lending their expertise to help design electronics for submillimetre satellite-based polarimeters and have formed a partnership with NIST for the continued develpement of large format arrays.

Martin Houde Canada Research Chair in Star Formation, Department of Physics and Astronomy, University of Western Ontario

Dr Houde's research concerns the study of molecular clouds and star forming regions, particularly on the role of magnetic fields during the different phases leading to stellar birth. He uses both spectroscopic and continuum observations to probe the physical conditions prevailing in star forming regions, as well as for characterizing the magnetic field. His research has shown that it is possible to combine polarization from the dust continuum and spectroscopic data to measure the inclination of the magnetic field in star forming regions; a first in the field. Dr. Houde is also an expert in the development of polarimeters for astronomical research. As such, he is a member of the team that has recently developed and commissioned the dual-wavelength Submillimeter High Angular Resolution Polarimeter (SHARP) for the Caltech Submillimeter Observatory, while the SCUBA-2 polarimeter is soon to be tested in his Submillimetre Laboratory at the University of Western Ontario. Dr. Houde is also part of a team led by Dr. Martin Harwit, Cornell University and HIFI/Herschel Mission Scientist, that plans to use Herschel to make polarization studies of masers in star forming regions. Dr. Houde possesses significant expertise in instrumentation design as he has previously spent many years as an Electrical Engineer in the aerospace industry before joining the Caltech Submillimeter Observatory, Hawaii.

The eventual wealth of data provided by SPICA in the MIR/FIR band, at the projected sensitivity, will be essential for determining the physical conditions (temperature, density, etc.) present in star forming regions. Many important molecular species (both simple and complex) and transitions are found in the FIR and can thus only be, or are better, observed from space. The same is true for the continuum emission from dust, here a number of wide and faint spectral features will necessitate the sensitivity and band coverage of SPICA for detection. This will be essential if we are to understand the evolution and composition of the dust in the Galaxy. The combination of these data sets will also enable to significantly improve our models for stellar births either at the low or high mass ends of the spectrum.

Doug Johnstone Senior Research Officer, National Research Council Canada, Herzberg Institute of Astrophysics and Associate Professor of Physics and Astronomy, University of Victoria

Dr. Johnstone's main research interest lies in how and where stars form inside molecular clouds and the process through which the collapse leads to disks and planets. Specific interest lies in constraining the theoretical models for star formation through the use of carefully selected observations. Expert in theoretical determinations of disk destruction, observational sub-millimetre continuum astronomy, and large-area mapping of star-forming regions.

The SPICA mission will be beneficial to the study of star formation due to its significantly increased sensitivity. This will be particularly helpful for his studies of structure in molecular clouds, piecing together the evolution from ambient material through core creation, collapse, and protostellar formation.

Gilles Joncas Professor, Department of Physics, Laval University

Dr Joncas has been studying the galactic interstellar medium since his PhD. He analyzed the interactions between massive stars and all aspects of the gaseous/solid state ISM (ionised, atomic, and molecular gas and dust). He has conducted spectroscopic and photometric observations from the visible and infrared through to the submillimeter and beyond. He actively uses the Canadian Galactic Plane Survey data banks (HI and CO) and he is deeply involved in the making of submillimetre surveys using the JCMT.

Dr Joncas has used the IRAS data abundantly, is a member of two Herschel Open Time key projects and is a member of the Planck working group 7 (LFI-CT). His interest lies in comprehending the physical processes and evolutionary scenarios involved in bringing the ionised gas expelled from stars back into stellar nurseries, the molecular clouds, from which the next generation of stars will be born. This implies the analysis of shocked regions, of the shedding of energy through cooling and turbulence, of the formation of molecules and the life cycle of dust grains.

The sensitivity and resolution of SPICA will provide access to the cool regions where H_2 is formed. As shown by previous space-based observations such as IRAS, COBE and ISO, the observation of the extended infrared emission highlighted the role of dust not only as a tracer of the interstellar medium (ISM) but also an agent in its ecology and evolution (for example as a catalyst for H_2 formation). Small dust particles (PAHs and VSGs) have been found to be ubiquitous components of dust, but with widely varying abundances relative to the classical big grains. SPICA is ideally tailored to provide access to the physics of VSGs and PAHs concurrently. The study of uniformly heated regions of the ISM, like the cirrus clouds, allows one to estimate the dust properties without any radiative transfer modeling. The combination of SPICA and JCMT data offers a unique opportunity to study the complete spectrum of dust emission with its three components : PAHs, VSGs and BGs. In particular, the relative abundance of these three components in relation to the dynamical history of the matter (from HI data) will allow Dr Joncas to investigate the coagulation and fragmentation processes involved in the dust evolution and determine how it could affect molecule formation.

At the other end of the physical spectrum, if H_2 is formed behind shock fronts in compressed dusty HI features its pure midIR rotational lines (28, 17, and 12 μm) can provide diagnostics of post-shock regions with temperatures as low as 100 K, giving access to *normal* interstellar clouds. The spectroscopy will give Dr Joncas information on how mechanical energy is injected, the origin and development of cloud turbulence and to place constraints on the thermodynamic properties of these regions; essential steps in developing a comprehensive model of the ISM.

Rene Plume Associate Professor, Department of Physics and Astronomy, University of Calgary

Dr Plume's research interests include the physics and chemistry of the interstellar medium, particularly as they relate to the formation of molecular clouds, stars, and planets. Recent interests include numerical modeling of astrochemistry. He is an expert in millimeter and submillimeter observations and analysis of molecular gas in the interstellar medium. Moreover, Dr Plume has extensive background in space missions including 6 years as a research scientist on NASA's SWAS satellite and a member of the Canadian ODIN team. He is also a member of the Canadian Science Steering committee for Herschel/HIFI.

SPICA's high resolution and sensitivity will directly impact our understanding of the chemical evolution of star formation through its ability to determine the oxygen budget as a function of position within collapsing clouds and circumstellar disks. The oxygen budget is important, not only for the subsequent formation of life-impacting molecular species, but also because species like O and H_2O are vital coolants of interstellar gas. Thus, a study of their abundance can be used to determine the temperature structure in star forming regions.

SPICA's ability to study the evolution of dust in the ISM also directly impacts our understanding of the first stage of star and planet formation: i.e. the formation of molecular clouds themselves. It is now well accepted that the formation of H_2 in the ISM does not occur in the gas phase, but on the surface of dust grains through the process of grain-surface chemistry. This process, however, is relatively slow at the typical temperatures and densities that characterize the atomic ISM. Recent work suggests that H_2 formation may occur more rapidly than previously thought if the grains are larger than "average" and complex in shape. SPICA will provide a unique tool for the study of how large grains can be produced through the coagulation of smaller grains, currently a poorly understood phenomenon, yet one that may be key to illuminating how molecular clouds form and ultimately collapse to form stars and planets.

Douglas Scott Associate Professor, Department of Physics and Astronomy, UBC

Dr Scott is a theoretical and observational astronomer with a particular interest in the far-infrared, millimetre-wave and microwave wavebands. He has worked extensively on the Cosmic Microwave and Infrared Backgrounds, and the study of distant, early star-forming galaxies through their unobscured emission at long wavelengths. He has been a Co-Investigator for the Planck satellite, as well as being on the Science teams for the BLAST balloon programme and Associate Scientist on the Herschel/SPIRE instrument.

He led a small team developing Quick Look software for Planck LFI instrument, and is also the scientist leading the development of Data Reduction Software for the ground-based sub-mm camera, SCUBA-2. There is great synergy between his scientific interests and SPICA/ESI, as well as the real possibility of being involved in Canadian software deliverables for this exciting new mission.

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