



DESCRIPTION OF INFRASTRUCTURE PROJECT

Date : 12/03/2009

Project Number : 23225

Institution : University of Calgary

Language of application : ☒ English ☐ French

Descriptive Title of Infrastructure Project (no more than 200 characters) :

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

Funding program

and stream : Leaders Opportunity Fund - Funding for research infrastructure alone

TOTAL COST OF INFRASTRUCTURE PROJECT AND AMOUNT REQUESTED FROM THE CFI

Note that for each year the CFI request should not exceed 40% of the cumulative cost to that year.

Costs	Year 1	Year 2	Year 3	Year 4+	Total
Total project	409 579	588 236	197 026	39 988	\$1,234,829
Partner contributions	279 789	342 601	98 513	19 994	\$740,897
CFI Request	\$129,790	\$245,635	\$98,513	\$19,994	\$493,932

DESIGNATED PROJECT LEADER

Name : Plume, René

Telephone 403 220-6909 Ext.:

Title : Associate Professor

Fax : 403 289-3331

Department : Physics & Astronomy

E-mail : plume@ras.ucalgary.ca

KEY WORDS

Provide a maximum of ten (10) words that describe the infrastructure project and the research to which it will contribute. Use commas to separate each key word.

radio astronomy, instrumentation

Research discipline/field code:

Primary : 12500

Secondary :

Area of application code :

Primary : 9.1

Secondary : 9.5

SIGNATURE

It is agreed that the general conditions governing the partner contributions and the use of CFI funds as outlined in the Institutional Agreement and the CFI Policy and Program Guide apply to the infrastructure project outlined in this application and are hereby accepted by the institution.

Name : _____

(CEO or President of the institution or authorized representative)

Signature : _____

Date : _____

Institution and title of infrastructure project (from page 1 of this module) :

Project Number : 23225

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

PROJECT OVERVIEW

Radio telescopes have, historically, been single pixel devices, which have made them terribly slow and inefficient instruments for examining the large scale radio emission from the Galaxy and the Universe (i.e. they have been "cameras" with only one pixel). The advent of focal plane arrays (FPA) on single dish radio telescopes, however, has changed this. Using a variety of different technologies, radio telescopes are now being equipped with these camera-like instruments that allow us to map larger areas of the sky than ever before, in reasonable amounts of time.

The US's National Radio Astronomy Observatory's (NRAO) Green Bank Telescope (GBT) is the largest, fully steerable, single-dish radio telescope in the world (~ 100 meters in diameter) and is also being equipped with an FPA to operate in the important K-band range of radio frequencies (18 - 26 GHz). This device (hereafter called the KFPA) is a state-of-the-art 7-pixel feed horn array capable of operating simultaneously at two orthogonal polarization states (i.e. 14 "channels"). It will also be extremely broadband, capable of detecting radio emission over a 1.8 GHz range at any given tuning within the K-band regime. The KFPA will provide new capabilities and will have an immediate impact on GBT science, such as:

- 1) It will speed up many observations by more than an order of magnitude, thus allowing experiments to be done, which could never, in practice, be scheduled with a single pixel receiver.
- 2) It will make the most efficient use of the restricted observing time available at low declinations (e.g., toward the Galactic Center and inner Galaxy) and of the limited good weather conditions at Green Bank. For example, nearly 450 hours were requested for K-band mapping projects in the last full trimester call for GBT proposals; most could not be scheduled, but with the KFPA they all would have been.
- 3) It will allow for more serendipitous discoveries by increasing the areas of maps.

Initially, the KFPA will be used with the current GBT Spectrometer. However, this will support only a 50 MHz instantaneous bandwidth for each of the 14 channels - much narrower than the 1.8 GHz of which the KFPA is capable. Thus, a new spectrometer, that would deliver the full 1.8 GHz instantaneous bandwidth per channel, is critically needed in order to exploit the full potential of the KFPA.

In this proposal, Dr. Plume & Dr. Taylor propose to develop a new spectrometer using a next generation signal processing system based on Field Programmable Gate Array (FPGA) based computing, technology which is being pioneered in Canada through a partnership between Lyrtech Signal Processing of Quebec City, the University of Calgary and the Dominion Radio Astrophysical Observatory (NRC-DRAO). This spectrometer would match the 1.8 GHz bandwidth of the KFPA in each of the 14 channels, thus maximizing the usefulness of the KFPA itself, and allowing Dr. Plume & Dr. Taylor to accomplish specific science goals:

- 1) To obtain the temperature and density structure of 10,000+ star forming regions in the

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

Galaxy that will be uncovered by upcoming surveys by SCUBA-2 at the James Clerk Maxwell Telescope and by the Herschel Space Observatory. This will, for the first time, place astronomers' understanding of the process of forming massive stars on firm statistical ground. Knowledge of this process is crucial to understanding galaxy evolution since massive stars are vital for energizing the interstellar medium, regulating the rate of star and solar system formation, and producing heavy elements. Despite this importance, knowledge of the process of massive star formation is poor due to their extreme rarity.

- 2) To obtain a chemical inventory of important molecular species in a large sample of star forming regions at different evolutionary stages and determine if there is a chemical "fingerprint" for the different phases of star formation and for stars of different mass.
- 3) To study magnetic fields in the universe through polarization observations of synchrotron radiation at radio wavelengths. These observations will help us study the magnetic fields of disk galaxies very much like the Milky Way, in Active Galactic Nuclei (the most energetic objects in the Universe), and to determine the contamination of the Cosmic Microwave Background (CMB) caused by extragalactic point sources (vital to the Planck mission's observations of the CMB).

Funding for the construction of the KFPA spectrometer has several benefits for Canada. First, it will develop key expertise and leadership in Alberta in technology development for future radio telescopes. Second, the K-band array on the GBT will be the most powerful facility of its kind in the world, offering a combination of angular resolution and sensitivity for rapid-imaging at 20 GHz that far exceeds any other capability. Therefore, it will also help keep University of Calgary researchers at the forefront of astronomy since the research that will be made possible by the proposed infrastructure will greatly enhance the scientific exploitation of other projects that are of high priority to Canadian Astronomy (such as the soon-to-be launched Herschel Space Observatory and Planck Cosmic Microwave missions). It also offers the first possibility to explore the polarization properties of extragalactic radio sources in this frequency regime in an unprecedented and statistically significant fashion down to faint flux densities.

Technological benefits to Canada include extending Canadian expertise of correlator technology and keeping Canada at the forefront of advanced digital systems. Lyrtech Signal Processing of Quebec City is a world leader in digital systems. In collaboration with the University of Calgary and the National Research Council's Dominion Radio Astrophysical Observatory (near Penticton), Lyrtech is currently building one of the most advanced digital signal processing systems in the world. This technology will be necessary for building next-generation phased-array beam-forming correlation spectrometers for future radio telescopes like the Square Kilometer Array (SKA), a project in which the University of Calgary is also playing a leading role. The proposed infrastructure project extends these successful collaborations and pushes the boundaries of digital processing technology by developing the next generation of such hardware integrated with next generation of software development tools.

Institution and title of infrastructure project (from page 1 of this module) :

Project Number : 23225

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank

Telescope's K-band Focal Plane Array Receiver

QUALITY OF THE RESEARCH OR TECHNOLOGY DEVELOPMENT

The proposed research or technology development is of high quality and originality, and meets international standards. It will create knowledge or develop technology leading to innovation.

1. Background - The Revolution in Focal Plane Array Receivers

The advent of focal plane arrays on single dish radio telescopes has opened up new areas of research, as demonstrated most recently with the Parkes 13-beam array at L-band, the FCRAO Sequoia 32-beam array at 85-116 GHz, and SCUBA at the JCMT. A K-band focal plane array (hereafter called the KFPA) for NRAO's Green Bank Telescope (GBT), which will uniquely cover the important 18-26 GHz band, will likewise provide new capabilities with immediate impact on GBT science. For example, this new array will provide vastly improved mapping capabilities (in both speed and sensitivity) which will allow astronomers to map much larger regions of the sky. This ability to look at the "Big Picture" will provide an improved understanding of global processes in the Galaxy, and a wealth of new data which will improve statistical studies of astronomical systems (star formation, magnetic fields, interstellar masers, pulsars, etc.).

2. The Infrastructure Development to be Undertaken

The current focal plane array development program at GBT is underway and consists of a 7-pixel dual-polarization (i.e. 14 channels) K-band (18-26 GHz) feed-horn array with 1.8 GHz of instantaneous bandwidth per channel. Initially, the KFPA will be used with the current GBT Spectrometer. However, this instrument will support only a 50 MHz bandwidth for each of the 14 channels, or wider bandwidths for a smaller subset of the channels. To exploit the full potential of the KFPA, a new spectrometer that would deliver the full 1.8 GHz instantaneous bandwidth per channel is critically needed. Dr. Plume and Dr. Taylor propose to develop this new spectrometer using a next generation signal processing system based on Field Programmable Gate Array (FPGA) - based computing, technology that is being pioneered in Canada through a partnership between Lyrtech Signal Processing of Quebec City, the University of Calgary and the Dominion Radio Astrophysical Observatory (NRC-DRAO). This spectrometer must meet the following specifications: 1) 14 channels (7 pixels, dual polarizations), 2) Sampling bandwidth of 3.6 Giga-samples/second with 4-8 bit sampling, 3) 1.8 GHz bandwidth, 4) Sub-banding to look at multiple narrow lines in each channel. In addition, this system is needed in less than 3 years.

Since this new spectrometer will be a common-user device, it is a requirement that it conforms to established Green Bank monitor and control interfaces, and is fully supportable by Green Bank staff once delivered. Since, in the future, NRAO intends to expand the KFPA to ~ 100 pixels, and also develop focal plane arrays to operate with wider instantaneous bandwidth, it is highly desirable that the new spectrometer architecture be scalable, and provide a basis for future significant expansion. The proposed correlator design provides this scalability.

3. Why the Proposed Activities are Considered Innovative

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

3.1. Technical Innovation

Digital systems evolve quickly and it is now possible to enhance existing telescopes, such as the GBT, by at least an order of magnitude with a modest investment in hardware. The dominant cost to implementing such systems is the engineering and development time. New tools are available that minimize this effort and make it easier to develop high-performance systems. Lyrtech Signal Processing is a leader in integrating such tools with digital systems. To date, such tools have not yet been fully implemented on large systems such as those required in Radio Astronomy. NRC-DRAO and the University of Calgary are world leaders in Radio Astronomy digital systems and are collaborating on projects such as low-noise amplifiers, calibration/processing techniques, and digital filter design in conjunction with the Square Kilometer Array (SKA) project, the world's premier, next-generation radio telescope (expected to begin operations in 2016). This proposed project leverages these strengths and brings together the technical expertise of Lyrtech, NRC and University of Calgary to develop next-generation hardware integrated with next-generation development tools as well. Just as compilers made programming general purpose computers easier, this project will be a first step in that direction for Field Programmable Gate Array (FPGA) based computing. The system developed will have broad utility in FPGA computing generally and find application in adaptive optics, digital filtering and beamforming, and pulsar processing as well as other applications where other approaches are either not powerful enough or cost effective. Moreover, this next-generation design is a pathfinder to the type of system that will be required by the Square Kilometer Array.

3.2. Research Innovation

While the KFPA will be useful to astronomers worldwide for a variety of scientific projects, the current spectrometer at GBT has strict limitations, especially for the science goals of astronomers at the University of Calgary. In particular, Dr. R. Plume & Dr. A. R. Taylor have very specific projects that require much broader bandwidth than the current spectrometer allows. These are summarized below.

3.2.1. Research Goal #1 - Understanding Massive Star Formation

Massive star formation plays an integral role in the evolution of galaxies because massive stars are responsible for energizing the interstellar medium (McKee 1986), producing the heavy elements (Dopita 1991), and may regulate the rate of star formation (McKee & Tan 2003). Despite its importance, massive star formation is a difficult topic to address. This is primarily due to the fact that massive stars are rare. For example, using simple assumptions Lumsden et al. (2002) calculated that there are about 2000 young stars in the Galaxy with masses greater than 12 solar masses. The same calculation for the very highest mass objects (Mass > 50 solar masses) predicts that there are only 20 or so in the entire Galaxy. Hence, to find these rare but crucial stars, requires a search of a substantial fraction of the whole Galactic Plane. In addition, since astronomers are interested in the initial conditions for the formation of massive stars, these surveys need to be performed at far-infrared and submillimeter wavelengths, where emission from cold, dense interstellar gas that forms these stars is brightest. This is precisely the goal of two large survey programs: the JCMT Galactic Plane Survey (JPS) and the Herschel Infrared Galactic Plane Survey (Hi-GAL) - for both of which Dr. R. Plume is a leading investigator.

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank

Telescope's K-band Focal Plane Array Receiver

The JPS is one of seven approved "Legacy" surveys to be done with SCUBA-2, the new sub-millimeter wavelength camera installed at the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. Hi-GAL is a recently approved Open Time Key Project that will be done using the Herschel Space Observatory. Both surveys are complementary and will map a substantial fraction of the Galactic Plane from the near-infrared to the submillimeter in an attempt to find a statistically significant number of cold, dense regions in the earliest phase of massive star formation. The addition of observations from the GBT's new KFPFA and the proposed Canadian digital spectrometer, however, will substantially enhance the scientific value of these important surveys by revealing the relevant physical and chemical conditions of massive star formation.

3.2.1.1. Physical Conditions

While both Hi-GAL and the JPS will observe the dust continuum emission from the Galaxy and help determine the location and density profile of numerous star-forming cores, additional information about the core temperature structure is needed to fully characterize the initial and early stages of massive star formation. Ammonia (NH_3) is an ideal molecule for tracing dense regions and for deriving temperature in interstellar gas. Nitrogen-bearing molecules are quite resilient tracers of dense, cold gas, and from the multiple NH_3 inversion lines its rotational temperature can be derived and used to determine the kinetic temperature, density distribution, mass, kinematics and turbulence of a molecular cloud. NH_3 is often a much better tracer of physical conditions than CO and its isotopes, which suffer from opacity effects and potential freeze-out in cold, dense cores which can be difficult to estimate (Tafalla et al. 2002).

The ratio of the K-band (J,K) = (2,2) at 23.723 GHz to (1,1) at 23.694 GHz inversion transitions is a well-known diagnostic of the low temperatures characteristic of cold, dense cores. Since these lines are only separated by 29 MHz, they can be observed simultaneously with the current spectrometer. However, states with greater energy differences are better indicators of higher temperature and density regimes. To effectively measure the range of temperatures and densities in cores at different evolutionary stages (which may or may not already contain embedded protostars), requires simultaneous observations of several higher energy ammonia lines. Given that these different NH_3 lines will trace gas with different temperatures and densities, observing all these lines at once will also give a simultaneous probe of the kinematics in different "layers" of individual star-forming regions. Finally, the kinematic (i.e. velocity) information provided by the NH_3 observations (coupled with a kinematic model of the Galaxy) will be crucial to determining the distances to these clouds and can even help separate clouds viewed along the line of sight. The 1.8 GHz bandwidth of the proposed spectrometer will allow simultaneous observations of the following lines: (J,K) = (1,1) at 23.694 GHz, (2,2) at 23.723 GHz, (3,3) at 23.870 GHz, (4,4) at 24.139 GHz, (5,5) at 24.533 GHz, and (6,6) at 25.054 GHz. This range of transitions will provide sensitivity to gas temperatures ranging from ~ 10 K to 400 K.

3.2.1.2. Chemical Conditions

The physical evolution during star formation is also accompanied by chemical evolution that points towards the interplay of a multitude of chemical processes, including ion-

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank

Telescope's K-band Focal Plane Array Receiver

molecule reactions at low temperatures in dark cloud cores, accretion and reaction on cold dust grains, and evaporation once the newly formed star turns on (e.g. van Dishoeck & Blake 1998). Thus, the observed chemical structure of a cloud gives unique information on the history of its physical conditions. Several important spectral lines that trace chemical processes fall within the 18-26 GHz band beyond NH₃ lines. CCS lines trace high density gas, but because CCS is chemically "young" (i.e. it is most abundant before atomic carbon becomes locked-up in CO), it can be used as a chemical clock when observed with NH₃ since, the higher the ratio of CCS to NH₃, the younger the region. In addition, H₂O Water maser emission is associated with the early stages of star formation. It originates in shocks and traces molecular outflows (Menten 1997). CH₃OH Methanol masers also trace outflows, perhaps at an even earlier stage in the formation of massive stars than H₂O does, and may be easier to interpret, as these masers are found exclusively towards massive star formation regions (Ellingsen 2005). Other molecules in this band include OCS which is related to shock chemistry, HC₃N, C₃S, HC₅N, and deuterated species such as DC₃N which can become effective tracers of the chemo-dynamical history of clouds.

Surveying a large number of star forming cores in the Galaxy, at different stages of their evolution and in different mass bins, will allow astronomers to determine if there are unique ratios of molecular species that characterize different phases of star formation. This is also one of the goals of the JCMT's Spectral Legacy Survey which is designed to obtain spectral scans of star-forming objects at 345 GHz (Plume et al. 2008), but which also has complementary data in K-band. The broad bandwidth of the proposed Canadian digital spectrometer will allow simultaneous observations of many of these spectral lines in K-band, thus maximizing the scientific return during the limited amount of suitable weather at K-band frequencies.

3.2.2. Research Goal #2 - Cosmic Magnetism

Magnetic fields in the universe are made uniquely visible through polarization observations of synchrotron radiation at radio wavelengths. The polarimetric imaging capability of the KFPA combined with the broad bandwidth of the Canadian digital spectrometer produces a powerful instrument for studying the polarization of radio sources at high radio frequencies. Three seminal studies would be carried out.

3.2.2.1. Deep Field

To probe the intrinsic polarization properties of active galactic nuclei (AGN), a deep polarization image of a small area of sky (about 1 square degree) to a sensitivity of 20 microJy would be made. AGN are the most powerful objects in the universe, powered by supermassive black holes at the centres of luminous galaxies. These objects are visible back to a significant fraction of the age of the universe. Magnetic fields play a strong role in the harnessing the energetic material emitted by such black holes. A deep radio survey of this kind with the GBT KFPA equipped with the 1.8 GHz spectrometer could be done in a few hundred hours and would detect as many as 2000 sources according to model counts by De Zotti et al. 2005. Such a survey would help us map out the evolution of cosmic magnetic fields through the variation of strength and degree of order of the radio source magnetic fields as a function of redshift (Gaensler 2007). In particular, a 20 GHz deep survey would help clarify the peculiar correlation found at lower frequencies that the

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank

Telescope's K-band Focal Plane Array Receiver

degree of linear polarization of a AGN increases with decreasing flux densities. Polarization at low radio frequencies is still affected by Faraday depolarization, while this effect becomes negligible at frequencies as high as 20 GHz. Thus the KFPA data would probe polarization properties in a way that will distinguish between intrinsic magnetic field evolution and evolution of the conditions that create internal depolarization from Faraday rotation processes, e.g. ionized gas associated with the central black hole engines.

3.2.2.2. Wide Area Survey

Determining the statistical polarization properties of extragalactic sources in K-band is also crucial in view of the scientific exploitation of high sensitivity and high resolution maps of the Cosmic Microwave Background (CMB) radiation (Hu & Dodelson 2002). Two major experiments (the current WMAP satellite and the Planck satellite due to be launched in 2009) are tackling the complicated issue of CMB polarization anisotropies. The power spectrum of these fluctuations, when combined with the total intensity fluctuations, provides a tool to determine important cosmological parameters (Seljak 1997) that reveal how the very early universe evolved. The CMB radiation is most intense at frequencies of several 10s of GHz. Such polarization fluctuations, however, are extremely weak (only a few percent of the total intensity of the Cosmic Background is polarized). Also, extragalactic point-like radio sources can mimic the CMB polarization signal, thus acting as a foreground contaminant. The statistical polarization properties of extragalactic radio sources and also which source populations would dominate the overall emission are not well known. A shallow (3 mJy) wide-area (half-steradian) survey with the K-band array can be carried out in 300 hours, once equipped with the Canadian digital spectrometer. In addition to complementing the information on AGN polarization from the Deep Survey by providing large numbers of stronger sources, these data would allow the CMB polarization foreground contamination from extragalactic point sources to be characterized.

3.2.2.3. Disk Galaxies

Recent work on integrated radio polarization of disk galaxies (Stil et al. 2008) has shown that radio polarization is a powerful probe of the properties of the global magnetic field in galaxy disks, and is related to indicators of star formation activity. Such studies offer the promise of insights into the relationship of global fields in galaxies and their star formation histories. With the KFPA and the Canadian digital spectrometer, astronomers can expect to observe the polarized synchrotron emission of spiral galaxies virtually unaffected by the effects of Faraday rotation. The nonthermal flux of spiral galaxies exceeds the thermal flux for frequencies less than approximately 30 GHz (Condon & Yin 1990), so K-band data are therefore well suited to study polarized emission in galaxies at high inclination. The advantage of high-frequency observations of edge-on galaxies was best illustrated by the 23-GHz WMAP polarization image of the Galaxy that showed the large-scale magnetic field in the disk, as well as some local magnetic structures unaffected by Faraday rotation.

4. How the proposed Activities Complement or Differ from Comparable research and Technology Development Elsewhere

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

The Canadian digital spectrometer, and the research that it would allow, complements the technical and research goals of several different facilities and yet does not duplicate any of them. For example, the spectrometer clearly complements the research and development that NRAO has placed into building the K-band focal plane array. It also builds on the considerable investment that the University of Calgary and NRC-DRAO have put into SKA-related technology. Furthermore, it helps keep a Canadian company (Lyrtech) at the forefront of these advanced digital systems.

Scientifically, the research that will be capable with the new spectrometer complements the scientific goals of many other ground- and space-based projects, as well as the the high resolution K-band observations that will be obtainable from the EVLA. Observations such as those proposed here have been successfully carried out by a number of authors (e.g. Rosolowsky et al. 2008). Given the limitations of current telescopes, however, such observations have been restricted to relatively small numbers of objects (i.e. a few hundred) and so a systematic survey of physical conditions in the few thousand objects uncovered by the recent far-infrared and submillimeter wavelength surveys has never been performed. Moreover, the 10,000+ objects expected to be uncovered by SCUBA-2 and Herschel Space Observatory will absolutely require the KFPA and the proposed spectrometer. These data will, for the first time, place the understanding of star formation on firm statistical ground. The KFPA also complements the research being carried out by the MOPRA telescope in Australia, although it will do so for the northern sky (which is not observable from Australia) and with a spatial resolution which is 4 times better than that achievable by MOPRA. The work done with the KFPA will also identify interesting sources that can be followed up at considerably higher resolution by the EVLA and, later, by the Atacama Large Millimeter Array (currently under construction).

For polarization studies, the K-band array on the GBT will be the most powerful facility of its kind in the world, offering a combination of angular resolution and sensitivity for rapid-imaging at 20 GHz that far exceeds any other capability. It offers the first possibility to explore the polarization properties of extragalactic radio sources in this frequency regime in a statistically significant and complete fashion down to faint flux densities. No other facility can do this. The EVLA, which has similar total collecting area, has too high angular resolution to detect the total radiation from these objects and the diffuse sky.

5. Why it is Critically Important to Pursue the Opportunity at this Time

Given that the GBT K-Band array is expected to be completed by 2010, it is crucial that construction of the broadband Canadian digital spectrometer begin as soon as possible to take full advantage of the data in a timely fashion. In addition, both SCUBA-2 and Herschel are expected to begin operations by Fall 2009. Finally, KFPA imaging data on the polarization properties of the sky at 20GHz will be critical to the assessment of foreground contamination emission for the Planck CMB mission which will launch in mid 2009 and produce first CMB images on the time scale of 2010/11.

Institution and title of infrastructure project (from page 1 of this module) :

Project Number : 23225

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank

Telescope's K-band Focal Plane Array Receiver

RESEARCHERS

1. List the researchers who will use the infrastructure. Add one additional page if required. This list may include researchers from non-eligible organizations.
2. Provide a CV module for each of the candidates essential to the justification of the project (the CFI will accept up to 3 CV modules).

Researcher (name and title)	Affiliation (department or faculty and institution)
Candidate(s) : Plume, René Associate Professor Taylor, Andrew Professor Other users :	Physics and Astronomy University of Calgary Physics and Astronomy University of Calgary

Institution and title of infrastructure project (from page 1 of this module) :

Project Number : 23225

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank
Telescope's K-band Focal Plane Array Receiver

RESEARCHERS (continued)

Compared to researchers at the same stage of their career in Canada and internationally, the past contributions and current plans of the candidate(s):

- demonstrate excellence, creativity, and leadership in the proposed research field(s), OR
- demonstrate potential for excellence, creativity and leadership in the proposed research field(s).

Dr. Plume is an expert in the fields of submillimeter radio astronomy and molecular astrophysics, and has been an active researcher for over 20 years. Currently, he is playing a leading role in a number of large, international collaborations involving surveys using both ground- and space-based telescopes. These are:

- 1) The JCMT Galactic Plane Survey (JPS) - which will use SCUBA-2 to survey the Galaxy at 850 microns.
- 2) The Herschel Infrared Galactic Plane survey (HIGAL) - which will use the Herschel Space Observatory to survey the same region covered by the JLS, but in many more mid to far infrared wavebands.
- 3) The JCMT Spectral Legacy Survey (SLS) - which will use the JCMT's heterodyne array receiver (HARP) to map all the molecular line emission within the 345 GHz atmospheric window within a sample of massive and low mass star forming regions.

Given Dr. Plume's roles in these projects, he is well positioned to make good use of the respective data products in a timely manner, and synchronize observations with the GBT's K-band array to maximize the science return of all the projects. For example, he will use the results from both the JLS and HIGAL to target followup ammonia observations of cores at the GBT, and correlate their physical conditions with their position within the Galaxy to look for the effect of Galactic environment upon star formation. In addition, the spectral line maps that can be produced for the SLS sources will also help trace the complex chemistry within the envelopes of low-mass and massive star forming regions and can extend these surveys to many other sources. Plume will lead the star formation/molecular spectroscopy component of the proposed activities including the software development for the needed observing modes and data processing & visualization.

Dr. Plume's creativity and excellence in the the field of Interstellar Medium/Star formation studies is evidenced by his large number of publications over his 20 year career (over 50 in refereed journals) and significant citation rate (greater than 1000). He has also served on numerous policy and science advisory committees such as the Board of Directors for the James Clerk Maxwell Telescope and for the Canadian Astronomical Society, the Canadian Science Steering Committee for the HIFI instrument aboard the Herschel Space Observatory, and is a member of the Canadian Space Agency's Far-Infrared Discipline Working Group. Dr. Plume was also the Director of the University of Calgary's Rothney Astrophysical Observatory (2004-2006) and helped guide the observatory towards its current role as a highly successful Education and Public Outreach facility. He has also received a number of awards, the most recent of which (2005) was NASA's Group Achievement Award for his work with the Submillimeter Wave Astronomy Satellite. On the instrumentation side, in 1995 Dr. Plume was awarded the International Union of Radio Science (URSI) student award for his design and construction of an innovative set of folding optics which converted the

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

10 meter diameter Caltech Submillimeter Observatory into a 1 meter telescope allowing him to map neutral atomic carbon emission over large regions of the sky.

Taylor is the director of the newly formed Institute for Space Imaging Science (ISIS) - a joint institute between the University of Calgary and the University of Lethbridge. He has extensive experience in the interface between science and technology in radio astronomy, with a history of leading major projects in radio astronomy. He has served on numerous national and international committees and advisory boards. Among these are several that impact planning and development of astronomy in Canada, including service as founding Executive Secretary of the International Square Kilometre Array Steering Committee, founding chair of the International SKA Science Advisory Committee, President of the Canadian Astronomical Society, chair of the Canadian Joint Subcommittee on Space Astronomy, and chair of the Canadian Radio Astronomy Committee. He is currently Canadian national Project Scientist for the Square Kilometre Array and chair of the Board of Directors of the Canadian SKA Consortium. He is also the incoming President of the Division of Radio Astronomy of the International Astronomical Union.

Taylor has published over 200 professional scientific articles, and has edited four books.

During his time as a professor at the University of Calgary he has mentored over 50 young scientists in radio astrophysics and the techniques of radio imaging of the sky. One was awarded the Henri Chrétien International Research Award from the American Astronomical Society in 1993 for work carried out under his supervision, and one graduate student was awarded the Canadian Astronomical Society's Plaskett Medal for the best Canadian Ph.D. thesis in Astronomy.

Taylor is the project leader of the CFI award for a North American Program in Radio Astronomy, which provides \$7.9 M for Canadian participation in ALMA and a framework for continued partnership with the United States on collaboration in the future of radio astronomy, including the Expanded Very Large Array (a major upgrade to the Very Large Array in New Mexico) and the Square Kilometre Array. As part of this CFI project he leads the Canadian software development project for the Atacama Large Millimeter Array. For the last several years he has led the Canadian Galactic Plane Survey and the International Galactic Plane survey projects, an international collaboration involving over 60 researchers which has secured large blocks of observing time on the world's most powerful radio telescope arrays to creating a detailed three-dimensional image of the Milky Way Galaxy. The Canadian Long Range Planning panel noted in its report that "the CGPS is an exemplary project for its scientific impact upon our knowledge of the Galactic interstellar medium, the extensive collaborative links between NRC and universities that it has fostered, and the training of a new generation of radio astronomers in this country."

Taylor's experience in managing and leading large projects will be extremely beneficial to the smooth progression and management of this project.

Institution and title of infrastructure project (from page 1 of this module) :

Project Number : 23225

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

NEED FOR THE INFRASTRUCTURE

The infrastructure is essential and appropriate for the proposed activities.

The digital spectrometer will be installed on the 100-meter Green Bank telescope (GBT) operated by the National Radio Astronomy Observatory (NRAO) in West Virginia. The GBT is the largest fully steerable telescope in the world and, therefore, has the highest resolution and sensitivity at the frequencies at which it operates. It uniquely offers the capabilities required for the science goals described in this proposal. While the Arecibo telescope has the capability to obtain polarization measurements, it does not have the required broadband spectrometer or high frequency capability for the Ammonia and molecular line observations. In addition, Arecibo is not fully steerable and so is limited to what it can observe in the sky. The MOPRA telescope in Australia does have the broadband spectral line capability. Due to its location in the southern hemisphere, however, it can only observe the southern part of the sky. More significant, MOPRA is only a 22-metre telescope and thus has much lower sensitivity and spatial resolution compared to the GBT. By building the proposed spectrometer for the GBT's K-band Focal Plane Array, University of Calgary astronomers will be able to accomplish their stated research goals, using the largest and most sensitive radio telescope in the world.

Access to the GBT and its new K-band Array receiver itself is not enough. The proposed Canadian digital spectrometer is absolutely essential to fulfill the research goals laid out in this proposal. Mapping the physical & chemical conditions in 10,000+ cores that are expected to be uncovered by the JPS and Hi-GAL will require both the KFPA (to obtain the spatial distribution of the radio emission) as well a spectrometer which can cover its full bandwidth. In addition, the polarization measurements needed to study cosmic magnetic fields also require an instrument with a much broader bandwidth than is currently available at the GBT. The University of Calgary is preparing a memorandum of understanding with NRAO that outlines its contribution to the KFPA project. In addition, under this agreement, there will be mechanism in place by which University of Calgary astronomers will have access to large amounts of observing time at the GBT through Key Projects.

All of the individual components that go into the construction of the Canadian Digital Spectrometer are also vital to the successful implementation of this project. Obviously, the HEX FPGA and Giga-sampler boards (Line items 3 - 6) are core components of the spectrometer, as is the chassis in which the boards are housed (Line item 8), and the engineering effort required to design them and assemble the finished product (Line item 1 & 2). The HEX FPGA software provided by Lyrtech (Line item 7) provides the basic "operating system" for the FPGA boards which will allow users to implement their own customized scientific algorithms. Lyrtech will also program the FPGA boards with the basic algorithms needed for this infrastructure project (i.e. high-resolution, broadband spectroscopy). The fibre-optic network (Line item 10) is required in order to move the large datasets produced by the KFPA and the Canadian digital spectrometer back and forth between the University of Calgary's Institute for Space Imaging Sciences (ISIS) server room (which currently contains a cluster of fast, data processing computers) and the desktop computers (Line item 12) used by Dr. Plume, Dr. Taylor, and the graduate students

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

and post-docs who will be hired to work on this project. Prior to science operations, in order to successfully commission the infrastructure, test data sets will need to be produced to allow the successful implementation of scientific data reduction and visualization algorithms specific to the research projects outlined in this proposal. In addition to the data reduction and visualization algorithms, new observing modes will need to be implemented for the GBT using the KFPFA and the Canadian digital spectrometer. This will require simulations of the telescope/receiver/spectrometer system, which will also be performed using the ISIS computer cluster. There is, after all, no point in building hardware for a scientific instrument if one does not have the software to actually make it work! The personnel (Line item 9) are, therefore, also vital to the successful completion of this project. The graduate student and postdocs will be needed to produce the necessary data acquisition, reduction and visualization algorithms. It is important that this development take place concurrently with the development of the spectrometer in order to deliver a fully functioning instrument to the GBT and, thus, maximize its scientific return. The other graduate student would be a student in engineering who would work on the implementation of new and innovative software/firmware for the FPGA boards themselves. This development would provide enhanced functionality to the instrument above and beyond the basic capabilities delivered by Lyrtech such as the mitigation of radio frequency interference, which can be problematic at 18 - 26 GHz. Historically, such RFI has been removed by hand in the post-processing stage. However, given the computational power inherent in these new FPGA boards, such interference removal can be automated and performed extremely rapidly and efficiently in firmware.

Although Dr. Plume has not previously led a CFI-funded project, Dr. Taylor is the project leader on a CFI International Fund award entitled "The North American Program in Radio Astronomy" (NAPRA). NAPRA is the mechanism whereby Canadian astronomers secure access to the Atacama Large Millimetre Array (ALMA), currently under construction in the Atacama Desert in Northern Chile. The CFI award funds capital development at the ALMA site, plus scientific planning and software development in Canada. As part of this project Taylor leads and manages Canadian software development in partnership with teams in the US (NRAO) and Europe (ESO). This software development focuses on a) control and data acquisition (the so-called ALMA commons software system) and off-line scientific processing. This work, which will be completed in late 2009, provides a legacy of expertise in space imaging software that underpins a significant element of this infrastructure proposal.

Institution and title of infrastructure project (from page 1 of this module) :

Project Number : 23225

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank
Telescope's K-band Focal Plane Array Receiver

TRAINING OF HIGHLY QUALIFIED PERSONNEL (HQP) THROUGH RESEARCH

The infrastructure requested will create or enrich an environment that attracts high-quality trainees and imparts new high-level skills to HQP for research and other careers.

Construction of the KFPA, and the research that it will allow, will significantly contribute to the training of HQP at the University of Calgary within the Institute for Space Imaging Science. This training aspect of this infrastructure project is perfectly aligned with one of the key mandates of ISIS to "provide a rich training environment that is unique in Canada, for University of Calgary and University of Lethbridge students and young researchers to work at the interface of science and technology in radio astronomy."

For example, new software will be required to allow the spectrometer to interface with the K-band Focal Plane Array as well as with the telescope control systems. In addition, in order to accomplish the scientific goals outlined in this proposal, new data collection, reduction, visualization and analysis algorithms will be required. The combination of multi-pixel imaging from the receiver array and the broad bandwidth from the spectrometer produces a massive, multi-dimensional data set. Postdocs and graduate students working on this project will achieve cutting-edge and marketable experience in imaging science and digital systems. There is already one postdoc at the University of Calgary (Roberto Ricci) who is actively working on the KFPA project. It is estimated that a total of two post-doctoral researchers and one graduate student will be required to work on this aspect of the project and to complete it in time to deliver a fully functioning instrument to the GBT.

In addition, although Lyrtech will provide the spectrometer with all of the basic functionality for the stated research goals, the Calgary team will program additional and enhanced functionality into the system. Capabilities like advanced Radio Frequency Interference (RFI) mitigation will be programmed into the system after delivery from Lyrtech. Historically, such RFI has been removed by hand in the post-processing stage. However, given the large, multi-dimensional data sets that be produced by the imaging array, and the computational power inherent in these new FPGA boards, automated interference removal, which can be performed extremely rapidly and efficiently in firmware, will be developed. This type of project is an example of research program for a graduate student in engineering who will spend part of their time at DRAO working on the inclusion of such enhanced capabilities into the spectrometer.

Finally, in addition to the technical skills that will be developed, the research potential of the KFPA and the projects that the astronomers at the University of Calgary intend to undertake, will provide enough data for numerous undergraduate and graduate research projects and, thus, help prepare them for careers as productive researchers. This infrastructure project provides for the postdocs and graduate student an opportunity to work in a cross-sector development network, involving academia, government laboratory and industry, and gives them access to best-in-the-world instrumentation, and collaborations with researchers, engineers and technical staff at leading international institutions. The benefits of such contact cannot be overstated.

Institution and title of infrastructure project (from page 1 of this module) :

Project Number : 23225

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank

Telescope's K-band Focal Plane Array Receiver

COLLABORATIONS AND PARTNERSHIPS

The collaborations and partnerships required to ensure that the proposed activities can be pursued successfully are appropriate and already in place or under development. The infrastructure requested will further support existing collaborations and partnerships, and help create new ones where appropriate.

The University of Calgary and NRAO are developing the framework for an agreement and agreed in principle on the terms of the partnership through a formal expression of intent which will be signed by NRAO and Calgary on collaborative development of the K-band focal plane array systems. Calgary researchers are currently providing scientific leadership and participating in the design work of the hardware and software to meet the science goals for the instrument. The development of the Canadian digital spectrometer by the Canadian team will make us equal partners with NRAO in the instrument and enable benefits to Calgary and Canada. It should be noted that although the spectrometer will reside at the GBT, the University of Calgary will retain ownership of the instrument.

In addition, U of C and NRC-DRAO have a successful partnership on the development of low-noise amplifiers, calibration/processing techniques, and digital filter design specific to the Square Kilometre Array project. This proposal would build upon this highly successful partnership and extend the collaboration to the field of advanced digital signal processing.

This infrastructure project also maintains and strengthens a strong partnership with Lyrtech Signal Processing of Quebec City. Lyrtech is a world leader in digital systems and, in collaboration with the University of Calgary and NRC-DRAO, is currently building a digital system that will be useful for phased-array beam-forming correlation spectrometers and that is one of the most advanced in the world. This development is geared specifically for the University of Calgary and NRC-DRAO's involvement in the Square Kilometer Array. The proposed infrastructure project to build the Canadian digital spectrometer extends this successful collaboration and pushes the boundaries of digital processing technology by integrating the next-generation of such hardware with new software development tools in this area. This next-generation design will have signal processing capabilities beyond anything that exists today and is precisely the type of system that will be required by the Square Kilometer Array, a project in which the University of Calgary is already playing a leading role.

Finally, this infrastructure project continues and enhances collaborations between Dr. Plume and Dr. Taylor and their respective National and International colleagues. For example, the ammonia data that can be provided by the KFPA and the Canadian digital spectrometer will enhance the scientific value of both the JCMT Galactic Plane Survey and the Herschel Space Observatory's HiGAL Key Project, both of which are major international projects involving dozens of researchers from around the world. The proposed polarization studies will provide increased opportunity for collaborations between University of Calgary astronomers and those worldwide who are working on the soon-to-launch Planck CMB Mission.

Institution and title of infrastructure project (from page 1 of this module) :

Project Number : 23225

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank

Telescope's K-band Focal Plane Array Receiver

BENEFITS TO CANADA

The proposed activities have the potential to lead to:

- benefits to society, health, the environment, quality of life, or public policy; OR
- increased economic activity.

Funding for the construction of the Canadian digital spectrometer has a number of benefits for Canada. First, it will keep University of Calgary researchers at the forefront of astronomy, and develop key expertise and leadership in Canada in technology development for future radio telescopes. For example, the research goals of Dr.'s Plume & Taylor (as described in this proposal) cannot be achieved without the proposed Canadian digital spectrometer. Both projects require full utilization of the native 1.8 GHz bandwidth provided by the KFPA. Beyond these specific applications, however, this system will also have broad utility in FPGA computing in general. In fact, there is potential for a number of different scientific and engineering applications where other approaches are neither powerful enough nor cost effective, such as: adaptive optics, digital filtering of signals (like the radio frequency mitigation that will be built into this project), beamforming, and observations of millisecond pulsars. This next generation design is also a stepping stone to the type of system that will be required by the Square Kilometer Array, a project in which the University of Calgary is playing a leading role.

In addition to the specific research program in this proposal, the Canadian digital spectrometer provides a legacy instrument that will become available to all Canadian researchers. Under the North American Partnership for Radio Astronomy (NAPRA) agreement, Canadian astronomers are eligible to apply for time at any NRAO facility (including the GBT) as though they were national facilities and, thus, will have access to the KFPA and the Canadian digital spectrometer.

Technological benefits to Canada include extending Canadian expertise of FPGA based technology and keeping Canadian research institutions and private industry at the forefront of advanced digital systems. The proposed infrastructure project pushes the boundaries of digital processing technology by developing the next generation of such hardware integrated with next generation of software development tools. Being a unique instrument, the KFPA and the Canadian digital spectrometer will bolster Canada's worldwide reputation as a provider of advanced digital systems and a pioneer in astrophysical investigation.

Institution and title of infrastructure project (from page 1 of this module) :

Project Number : 23225

University of Calgary

The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank
Telescope's K-band Focal Plane Array Receiver

INTEGRATION WITH THE STRATEGIC RESEARCH PLAN

(To be completed by the Institution)

This infrastructure project is well aligned with the University of Calgary's Strategic Research Plan which, among other things, intends to "foster key areas of existing and emerging strengths and to undertake a broad range of research and scholarship in support of the educational mandate". The University of Calgary has internationally recognized strength in the field of radio astronomy. For example, Dr. Plume and Dr. Taylor are playing leadership roles in a number of large, international projects including Key Projects to be done with the Herschel Space Observatory and Planck Mission, as well as the development of technology crucial to the Square Kilometer Array. Development of the Canadian digital spectrometer will help keep the University of Calgary Radio Astronomy at the forefront of astrophysical research. The opportunities for graduate student (and even undergraduate) participation in the development of this project spectrometer and subsequent scientific return from the spectrometer are also aligned with the "educational mandate" of the Strategic Research Plan. The spectrometer will, ultimately, generate enough data for numerous student projects, providing University of Calgary students with valuable research and technological experience.

Four priority areas are identified in the University of Calgary's Strategic Research Plan, one of which has particular relevance to this infrastructure project, namely "Creating Technologies and Managing Information for the Knowledge Society". The Canadian digital spectrometer will push the technological boundaries in advanced digital signal processing on both the hardware and software sides. In combination with the multi-feed receiver system on the GBT it creates a world-leading RF imaging device. Commissioning and operating this device will develop or enhance expertise in several areas related to technologies and information management. Advanced, flexible digital systems will be vital to the next generation of radio telescopes and, indeed, will have practical applications in other areas of science and engineering, for example: adaptive optics, ultra-fast high time resolution signal processing, streaming processing of high bandwidth data, digital filtering of signals (e.g. excision and mitigation of interfering signals as intended for this project), visualization of and information/knowledge extraction from multi-dimensional (hyper-spectral) data. The scientific goals of this project also align directly with the Faculty of Science strategic research plan, which lists "Understanding the Evolution of the Universe" as one of its five priorities.

Development of new imaging technologies and systems for end-to-end use of new technology for space imaging and discovery are core to the mission of the Institute for Space Imaging Science (ISIS - a recently-formed joint institute between the U of Calgary and the U of Lethbridge). This project fits centrally within this mandate. Over and above the inherent value of the project for its stated technical and scientific goals, it has strategic value to ISIS in the expertise that will be developed. For example, the digital technologies that will be the platform for the spectrometer are the same as those that will be explored as part of the research and development for phased focal-plane arrays systems for the Square Kilometre Array.



Canada Foundation
for Innovation

Fondation canadienne
pour l'innovation

SUGGESTED REVIEWERS

Date : 12/03/2009

Project Number : 23225

Institution : University of Calgary

Designated Project Leader : Plume, René

Project Title : The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

Identify six reviewers appropriate for the application. Reviewers must not be current or recent (within the last six years) collaborators, departmental colleagues, students, or supervisors.

Provide a complete mailing address, telephone number, fax number, current e-mail address and the areas of expertise of potential reviewers. Suggested reviewers may be Canadian or international, and should be able to evaluate the application in the language in which it is written.

The CFI reserves the right to make its own selection of reviewers.

Name : Bastien, Pierre	Telephone : 514 343-5816 #
Address : Dept. de Physique	Fax : 514 343-2071
Université de Montréal	
C.P. 6128 Succursale Centre-Ville	
Montreal, QC	
Postal code : H3C3J7	E-mail : bastien@astro.umontreal.ca
Area(s) of expertise (key words) : astronomy	

Name : Heyer, Mark	Telephone : 413 545-4264 #
Address : Five College Radio Astronomy Observatory	Fax :
University of Massachusetts	
Lederle Research Tower	
Amherst, MA	
Postal code : 01003	E-mail : heyer@astro.umass.edu
Area(s) of expertise (key words) : astronomy	

Name : Bally, John	Telephone : 303 492-5786 #
Address : Astrophysical & Planetary Science	Fax : 303 492-7178
University of Colorado	
391 UCB	
Boulder, CO	
Postal code : 80309	E-mail : John.Bally@colorado.edu
Area(s) of expertise (key words) : astronomy	



Canada Foundation
for Innovation

Fondation canadienne
pour l'innovation

SUGGESTED REVIEWERS

Date : 12/03/2009 **Project Number :** 23225
Institution : University of Calgary
Designated Project Leader : Plume, René
Project Title : The Canadian Digital Spectrometer: A Next Generation Instrument for the Green Bank Telescope's K-band Focal Plane Array Receiver

Identify six reviewers appropriate for the application. Reviewers must not be current or recent (within the last six years) collaborators, departmental colleagues, students, or supervisors.

Provide a complete mailing address, telephone number, fax number, current e-mail address and the areas of expertise of potential reviewers. Suggested reviewers may be Canadian or international, and should be able to evaluate the application in the language in which it is written.

The CFI reserves the right to make its own selection of reviewers.

Name : Menten, Karl **Telephone :** 490 228 525297 #
Address : **Fax :** 490 228 525435
Max Planck Institut fur Radioastronomie
Auf dem Hugel 69
Bonn
Postal code : D-53121 **E-mail :** kmenten@mpifr-bonn.mpg.de
Area(s) of expertise (key words) : astronomy

Name : Tafalla, Mario **Telephone :** 34 91 527-0107 #
Address : **Fax :** 34 91 527-1935
Observatorio Astronomico Nacional
Alfonso XII 3
Madrid
Postal code : ES 28014 **E-mail :** m.tafalla@oan.es
Area(s) of expertise (key words) : astronomy

Name : Caselli, Paola **Telephone :** 44 113 3434065 #
Address : School of Physics & Astronomy **Fax :** 44 113 3433900
University of Leeds
E.C. Stoner Building
Leeds
Postal code : LS29JT **E-mail :** p.caselli@leeds.ac.uk
Area(s) of expertise (key words) : astronomy