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EXPERIMENTAL ASTROPHYSICS AND ASTRONOMICAL INSTRUMENTATION[1,2]

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1. PAST AND CURRENT ACTIVITIES

Note that this overview is based on contributions collected from many individuals over the course of writing this white paper. Activities are listed in Table 2. Many of these are described in greater details in other white papers, and there are other activities under way that do not appear here.

1.1. *Radio Astronomy*

The University of Calgary node of the Institute for Space Imaging Science (ISIS), as well as NRC-HIA, has been identified as one of the 20 institutes world-wide with specific responsibilities for the development of prototype instrumentation for SKA. The ISIS RF Integrated Circuit group specializes in analog RF front-end receiver design. Their components are currently the best performing in the world. The ISIS Radio Astronomy division is developing the pipeline software for wide-field imaging and spectro-polarimetric imaging with the new multi-pixel receiver array on the Arecibo telescope. They are also developing software systems for ALMA and the EVLA for broad-band, full-Stokes, wide-field imaging from data with the new EVLA correlator.

NRC-HIA in Penticton has expertise in RF and large digital systems and is a strong contributor to SKA development. The group is leading the correlator work for the SKA, largely as a result of the EVLA correlator they have developed. When complete in Q1 2010 it will be the most capable correlator in the world. A legacy of this work is the development of a front-line engineering team that is capable of building large digital systems that are needed for next generation instruments such as the SKA. NRC-HIA is also working on composite antenna reflectors, which are the only technology demonstrated to date that are low cost and operate to 30 GHz. This technology is key to the SKA and is part of a larger collaboration with the US Technology Development Program to develop a prototype tested antenna for the SKA. Expanding the field of view of a telescope is valuable and the group is developing phased array feeds (PAFs) to do that. The work is highly complementary to Canadian SKA activities as it involves the RF IC and signal processing efforts at the University of Calgary.

NRC-HIA in Victoria has led ALMA instrumentation efforts through the development and fabrication of the Band 3 (85-116 GHz) receivers and is planning to develop the Band 1 (30-50 GHz) receivers as well as to work on key SKA technologies.

1.2. *Far-infrared and Submillimeter Astronomy*

The University of Lethbridge node of ISIS has built imaging Fourier transform spectrometers for the Herschel satellite and JCMT/SCUBA-2 and plans to build a similar one for the future Japanese SPICA satellite. Lethbridge also developed infrared instrumentation for site evaluation for the TMT, GMT and EELT.

The University of Waterloo provided the Local Oscillator Source Unit for HIFI on Herschel. Waterloo and nine other Canadian institutions are members of the Cerro Chajnator Atacama Telescope Canadian consortium. Waterloo is also part of two programs to put far-infrared interferometers in space (ESA FIRI and NASA SPIRIT). Work on detector development for the FIR and sub-mm is ongoing. UBC has developed electronics systems for SCUBA-2, ACT and CLOVER. It is now working on SPIDER and other related projects. The University of Montréal built the SCUBA-2 polarimeter, and the University of Western Ontario has been part of the team developing SCUBA-2 hardware.

The University of Toronto has played leading roles in two stratospheric scientific balloon missions, BOOMERANG and BLAST, and is participating in the BLAST-pol and SPIDER projects. These activities would not have been possible without a specialized high bay area where the testing of pointing systems and star trackers with a gondola is possible. The McGill team co-led the development of the SQUID-based multiplexed readout system for APEX-SZ and the South Pole Telescope, which is one of the key enabling technologies for instruments using large arrays of Transition Edge Sensors. Since then, the team developed a new digital multiplexed readout system that is being used for the EBEX balloon-borne polarimeter and POLARBEAR. McGill is involved with these experiments end-to-end.

1.3. *Optical and Near-Infrared Astronomy*

The University of Montréal and Laval have developed several techniques and instruments for the 1.6-m telescope at Observatoire du Mont Mégantic (OMM), CFHT and Gemini. These include near-infrared cameras (TRIDENT, KIR, CFHT-IR, WIRCam) on OMM and CFHT, a Fourier transform spectrometer for OMM, and the simultaneous spectral and angular differential imaging techniques. They also participate in instrument projects such as a tunable filter imaging system on JWST,

[1]Invited LRP2010 white paper
[2]A list of acronyms is provided in Table 1

the Gemini Planet Imager, an imaging FTS for CFHT (SITELLE), an optical polarimeter for OMM and CFHT, a Fabry-Pérot system (GHaFaS) for the WHT telescope, a low and high order Fabry-Pérot system for the 3.6-m NTT telescope and a low-noise, high-speed EMCCD controller. These efforts have stemmed from the successful collaboration of the Laboratoire d'Astrophysique Expérimentale (LAE) centered around the OMM and funded through NSERC, CFI, CSA, and FQRNT.

The University of Toronto has participated in the development of new broadband, near-infrared spectrographs for the Palomar 5-m, Apache Point 3.5-m and Keck 10-m telescopes. It is designing and building an image slicer-based Wide Integral Field Infrared Spectrograph (WIFIS) for 8-10m telescopes with an unprecedented combination of etendue and resolution. Toronto is the lead institution for the TMT AO science calibration system. Toronto is also responsible for the tunable filter system on Flamingos-2 at Gemini South. All these efforts are expected to be incorporated into the newly founded Dunlap Institute. Finally, the UofT Institute for Aerospace Studies has collaborated on micro- and nano- satellite missions such as MOST and BRITE.

The Herzberg Institute of Astronomy (HIA) has played a vital role in the development of instruments for CFHT, Gemini and TMT. It built the adaptive optics system and optical multi-object spectrographs for Gemini, and it is the lead institution for the TMT first-light adaptive optics system (NFIRAOS). The University of Victoria is working on new adaptive optics systems such as RAVEN, a multi-object adaptive optics demonstrator system to be installed at the 8-m Subaru telescope. The University of British Columbia (UBC) is actively participating in the TMT adaptive optics system. It is developing lidar systems to probe the mesopheric sodium layer that is key to laser-guide star AO observations, and site testing instrumentation for the Canadian Arctic.

1.4. *Ultraviolet Astronomy*

The Canadian Space Agency is contributing the UV detectors for the Indian ASTROSAT observatory, planned for launch in late 2010. ASTROSAT is a major observatory with scientific goals of X-ray timing, imaging and spectroscopy and associated UV observations. The UV Imaging Telescope (UVIT) consists of two telescopes with three detectors, for far UV, near UV and visible wavelengths. The detectors are MCP/CMOS based photon counting devices with $1''$ spatial resolution and several movable filters for wavelength discrimination. The detectors are being calibrated at the University of Calgary. Many Canadians are members of the science team.

1.5. *Very High-Energy Astronomy*

McGill University has participated in several international ground-based gamma-ray programs in the energy range from 100 GeV to 10 TeV. This includes the current VERITAS project of four 12-m telescopes in Arizona for which it has provided mirror facet fixtures, custom electronics, facet alignment system as well as an ultraviolet flasher system for PMT calibration. It is also participating in future projects such as the Advanced Gamma-Ray Imaging System and a Compton-scattering telescope.

2. MTR2005 RECOMMENDATIONS: HOW WELL DID WE DO?

The Committee for the Mid-Term Review (MTRC) of the first Long-Range Plan held in 2004-2005 re-affirmed a number of LRP recommendations. For the most part, instrumentation efforts in Canada have lived up to the project-related recommendations. Band 3 for ALMA is well on its way to completion, and the EVLA correlator is undergoing commissioning. Canada has secured a share of JWST with a leading role on the Fine Guiding Sensors and Tunable Filter package and representations on the NIRCAM and NIRSPEC science teams. Although Canada has not been able to take part in the Australian SKA pathfinder project, teams remain engaged in vital technology developments from new composite antennae to sensitive receivers. Canada has fulfilled its obligation as an equal partner in the Detailed Design Phase of TMT. The Lethbridge group built an instrument package (SPIRE) for the Herschel mission, and other (Canada-led) missions such as MOST and BLAST have been highly successful. NRC-HIA, Montréal and Laval are playing a key role in the only active Gemini instrumentation project (GPI), and they are also working on the next-generation instruments for CFHT. Shared-risk observations with SCUBA-2 have just started.

One of the strongest LRP recommendations on instrumentation was the building of university labs in experimental astrophysics. This recommendation was reiterated by the MTRC, and it went beyond new labs and equipment. It also explicitly stated that there should be commensurate increases in the numbers of university researchers in the area of instrumentation in both space and ground-based astronomy. As discussed in the next section, a stable level of human resources remain a significant challenge for instrumentation efforts in Canada.

3. OUTLOOK FOR THE NEXT DECADE

3.1. *Continuing Work on Major Projects*

The Canadian instrumentation community is actively involved in an impressive array of exciting projects: CFHT (IMAKA, SPIROU, SITELLE), GPI, TMT (NFIRAOS and IRIS), JWST FGS/TTF in the optical and near-infrared, JCMT SCUBA-2, ALMA Bands 3 and 1, and CCAT in the sub-mm/far-infrared and SKA in the radio. These major projects will likely require sustained efforts over an appreciable fraction of the next decade.

3.2. *Instrumentation Development Models*

One challenge for the next decade will be modifications to the instrumentation development models that instrument builders have used so far. Instrumentation communities must be able to match the scale of their efforts to the scale of their aspirations. This is not trivial. Different sub-communities have gone through transitions in their development model at different times. For example, it has been possible up to now for the sub-mm community to build instrumentation for the JCMT with relatively modest investments in people and equipment. Building a facility instrument for an observatory such as ALMA entails efforts on a entirely different scale. The optical/near-IR community went through a similar transition going from 4m to 8m-class telescopes.

Transition as used above has the connotation of "leaving something behind." Nothing could be further from the truth. The challenge is really to define the proper scope of Canadian efforts in a landscape of facilities that extends to ever larger and more complex observatories. There is a spectrum of options going from technology testbeds (e.g., RAVEN), to specific instrument subsystems (e.g., TMT calibration unit, SCUBA-2 polarimeter), to full visitor and facility instruments (e.g., ALMA Band 3). We are not proposing that the community should focus on a specific scale. It would be unwise to abandon smaller scale efforts such as testbeds because these often breed the "next great ideas" that propel the next generation of larger instruments. Similarly, it would be unwise to abandon larger scale projects given that leading edge science in many fields now demands ambitious facilities built by global consortia. The recommendations from the first LRP put most emphasis on large projects at major facilities. LRP 2010 should include more flexibility in this matter. The Canadian instrumentation community has clearly shown through its diverse range of activities that it wants to remain active on a wide range of project scales.

The choice of instrument development model has a direct impact on the structure of the teams involved. A testbed can be set up and operated with a few students under the supervision of one or two faculty members. Larger efforts require a diverse set of expertise, team continuity and rigorous project management and systems engineering. There are two main approaches to meeting these requirements. One is to build a relatively self-contained team. This approach can be powerful if the team can "matrix" across different projects over a significant number of years. The second approach is to establish close ties across science and engineering departments, across different institutions and across academia and industry. It is more natural for a university environment, but past experiences have shown that it is often surprisingly hard to build bridges across departments even within the confines of a single institution. Funding for a multidisciplinary program specifically targeted at astronomical instrumentation would go a long way towards breaking down artificial walls. Instrumentation research chairs with industrial components that were established at some universities have led the way here, but this type of initiative needs to be expanded. More frequent interactions (e.g., monthly tele-/video- conferences, annual instrumentation school) between instrumentation groups across Canada would also be welcome.

3.3. *Resources*

The need for concurrent funding of people and equipment is a particularly acute challenge for instrumentation efforts. This is not made easy by the well-known fact that different agencies independently fund different components of the requests they receive. CSA funds space missions, CFI funds equipment and facilities, NSERC tends to fund people at universities and provincial agencies fund a mixture of both. There is no coordination between funding decisions aside from the CFI requirement that matching funds be provided to all of their funded initiatives. This lack of coordination often throws instrumentation teams into situations where funding for equipment has been secured, but funding for personnel does not materialize or lags significantly. The "softness" of the funding has also impacted instrumentation groups at universities. More stable funding streams such as the ones supporting many European institutions would allow university teams to develop and retain their expertise as well as allow them to plan for longer projects in a more coherent way. It is worthwhile to note here the creation of two university-based centers in recent years to address many of the issues raised here. The Institute for Space Imaging Science (ISIS - Calgary, Lethbridge and Athabasca) and the Centre de Recherche en Astrophysique du Québec (CRAQ - Laval, McGill and Montréal) both bring complementary expertise together to seek continued funding and maintain capacity.

Training the next generation of instrument builders is obviously an important element of the human component in instrumentation for the next decade. Canadian teams have trained an impressive number of students, but getting involved in instrumentation projects may still appear daunting to future students for a number of reasons. Larger projects bring the perceived risk that they will find themselves involved in projects with longer timescales than their normal graduate school cycle. This is indeed a risk if not properly managed, but past experience has shown that students can assume leading roles in teams working on large projects. For example, undergraduate students on 4-month coop work terms have designed some key subsystems in the Gemini Planet Imager, the TMT AO system and ALMA Band 3 and have found the experience very rewarding. Sharing student experiences among Canadian instrumentation teams and fostering a student instrumentation network (through a special CASCA session?) would help students make the decision to pursue instrumentation as a career. Instrumentation as a valued career path remains an issue in Canada. In most cases the number of publications is the prime metric by which the scientific abilities of a candidate is measured in hiring decisions for postdoctoral researchers and faculty members at Canadian institutions. It is fair to say that the Canadian community is still struggling to define a metric that can be similarly applied to somebody who has primarily worked on instrumentation projects. Encouraging progress has been made on this problem over the last decade, but there is definitely room for improvement over the next one.

3.4. *New Technologies*

The aspirations of Canadian instrumentation teams for the next decade rest on a number of technological developments (to name a few):

1) Wavefront control in the optical/near-IR. New flavors of adaptive optics will include Multi-Object AO (MOAO) and extreme AO for the direct imaging of exoplanets. Deformable mirrors with higher actuator density, more sensitive wavefront sensors and more powerful real-time controllers will need to be built.

2) Wide-field, multi-object/integral-field spectroscopy (e.g., WIFIS) and hyperspectral imaging techniques using Fourier transform spectrometers (e.g., SAFARI, SPIRE, SPIOMM, SITELLE) in the optical/IR.

3) Detector development will be a major research thrust: i) Wide-field detectors for gamma-ray astronomy, ii) Large format, high QE photon-counting CCDs are likely to revolutionize high-resolution optical spectroscopy, iii) Controllers for EMCCDs that reduce clock

induced charges to a level that brings the readout noise down to essentially while keeping their high DQE, iv) Large TES sensors to fly on future CMB polarization instruments, v) Next generation, cryogenically cooled, ultra-sensitive detectors for far infrared imaging spectroscopy, and vi) Microwave Kinetic Inductance Detectors (MKIDS) to allow CCAT to map an area on the sky 2400 times faster than possible with ALMA.

4) Planar heterodyne arrays at THz frequencies with very stable local oscillators and precise metrology for spacecraft station keeping will be needed for space interferometry missions at far infrared wavelengths.

5) Radio frequency integrated circuits, low-noise amplifiers, focal plane array systems, and inexpensive feeds for signal detection over a very wide range of frequencies (e.g., 1-10 Ghz) will enable key SKA capabilities.

6) Fast digital signal processing electronics and data analysis techniques for new hydrogen intensity mapping missions such as CHIME.

TABLE 1
List of Acronyms

Acronym	Full Name
ACSIS	Auto-Correlation Spectrometer Imaging System
ACT	Atacama Cosmology Telescope
AGIS	Advanced Gamma-ray Imaging System
ALMA	Atacama Large Millimeter Array
APEX-SZ	Atacama Pathfinder EXperiment - Sunyaev-Zel'dovich
BLAST	Balloon-Borne Large-Aperture Sub-millimeter Telescope
BOOMERANG	Balloon Observations of Millimetric Extragalactic Radiation and Geophysics
BRITE	BRight Target Explorer
CCAT	Cerro Chajnator Atacama Telescope
CFHT	Canada-France-Hawaii Telescope
CFI	Canadian Foundation for Innovation
CHIME	Canadian Hydrogen Intensity Mapping Experiment
CLOVER	A UK B-mode CMB polarization experiment (recently cancelled)
CMB	Cosmic Microwave Background
CMOS	Complementary Metal-Oxide Semiconductor
CRAQ	Centre de Recherche en Astrophysique du Qubec
CSA	Canadian Space Agency
EBEX	E and B EXperiment
EELT	European Extremely Large Telescope
EMCCD	Electron Multiplying Charge Coupled Device
ESA	European Space Agency
EVLA	Extended Very Large Array
FIRI	Far InfraRed Interferometer
FGS	Fine Guiding Sensors (on JWST)
FQRNT	Fonds québécois de la recherche sur la nature et les technologies
FTS	Fourier Transform Spectrometer
GHaFaS	Galaxy H-alpha Fabry-Pérot System
GMT	Giant Magellan Telescope
GPI	Gemini Planet Imager
HARP	Heterodyne Array Receiver Programme (on JCMT)
HIA	Herzberg Institute of Astrophysics
HIFI	Heterodyne Instrument for the Far-Infrared
IMAKA	Imaging from MAuna KeA (on CFHT)
IRIS	InfraRed Imaging Spectrometer (on TMT)
ISIS	Institute of Space Imaging Science
JCMT	James Clerk Maxwell Telescope
JWST	James Webb Space Telescope
KIR	Adaptive optics-assisted, near-infrared camera at CFHT
LAE	Laboratoire d'Astrophysique Expérimentale
MCP	Microchannel Plate detectors
MKIDS	Microwave Kinetic Inductance Detectors
MOAO	Multi-Object Adaptive Optics
MOST	Microvariability and Oscillations of STars
NFIRAOS	Narrow Field InfraRed Adaptive Optics System (on TMT)
NIRCAM	Near-InfraRed Camera (on JSWT)
NIRSPEC	Near-InfraRed Spectrograph (on JWST)
NSERC	Natural Sciences and Engineering Research Council
OMM	Observatoire du Mont Mégantic
PAF	Phased Array Feed
PMT	Photo-Multiplier Tubes
POLARBEAR	Polarization of Background Microwave Radiation
RAVEN	MOAO demonstrator being designed and built at UVic AO lab. To be installed on Subaru telescope
SAFARI	SpicA FAR-infrared instrument (on SPICA mission)
SCUBA	Submillimetre Common User Bolometer Array (on JCMT)
SKA	Square Kilometre Array
SITELLE	Spectromètre Imageur à Transformée de Fourier pour l'Etude en Long et en Large de raies d'Emission (on CFHT)
SPICA	Space Infrared Telescope for Cosmology and Astrophysics (Japan)
SPIDER	Balloon-borne large-scale CMB polarimeter
SPIOMM	Spectro-imageur à transformée de Fourier pour l'Observatoire du Mont Mégantic
SPIRE	Spectral and Photometric Imaging Receiver (on Herschel)
SPIRIT	Space InfraRed Interferometric Telescope
SPIROU	Near-infrared échelle spectropolarimeter for CFHT
SQUID	Superconducting Quantum Interference Device
TES	Transition Edge Sensor
TMT	Thirty-Meter Telescope
TRIDENT	Infrared differential imaging camera optimized for the detection of methanated substellar companions
UVIT	Ultra-Violet Imaging Telescope
VERITAS	Very Energetic Radiation Imaging Telescope Array System
WHT	William Herschel Telescope
WIFIS	Wide Integral Field Infrared Spectrograph
WIRCam	Wide field InfraRed Camera (on CFHT)

TABLE 2
Current Canadian Activities in Experimental Astrophysics and Astronomical Instrumentation

Wavebands	Institutions	Projects/Facilities
Radio	U.Calgary	ALMA, EVLA, SKA, Arecibo
···	HIA	ALMA, SKA
Far-IR/Sub-mm	U.Lethbridge	Herschel, JCMT, SPICA, TMT, GMT, EELT
···	U.Waterloo	Herschel, SCUBA-2, CCAT, FIRI, SPIRIT
···	UBC	SCUBA-2, ACT, CLOVER, SPIDER
···	Montréal	SCUBA-2
···	UWO	SCUBA-2
···	U.Toronto	BLAST, BLAST-Pol, SPIDER, BOOMERANG
···	McGill	South Pole Telescope, APEX-SZ, EBEX, Polarbear, CHIME
Optical/Near-IR	U.Montreal	OMM, CFHT, Gemini, JWST, NTT, WHT, EMCCD controller
···	Laval	OMM, CFHT, Gemini
···	U.Toronto	Keck, Palomar, Gemini, TMT, MOST, BRITE
···	U.Victoria	Subaru, TMT
···	UBC	TMT, MOST
···	HIA	Gemini, TMT, CFHT
Ultraviolet	Calgary	UVIT
Gamma Rays	McGill	VERITAS, AGIS, Compton Scattering Telescope

Note. — Note that this is not a complete list. Different activities have different Canadian levels of participation.