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THE ATACAMA LARGE MILLIMETER/SUBMILLIMETER ARRAY

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ABSTRACT

The first Canadian Long Range plan identified the Atacama Large Millimeter/Submillimeter Array (ALMA) as the highest priority for a major ground-based observatory. With Early Science scheduled for 2011 and construction to be completed by 2013, ALMA is poised to deliver transformational science across a wide range of topics. **For the next five years, the most critical issues for Canadian participation in ALMA are (1) to secure complete Canadian funding for ALMA operations, and (2) to identify a visible role for Canada in ALMA operations.** Additional important issues are to prepare the Canadian community to be effective ALMA users, both in Early Science and in full operations, and to position Canada to lead or play a major role in one or more ALMA development projects. Finally, it is critical that the final construction funds be available to complete our Band 3 commitment.
Subject headings:

1. INTRODUCTION

The Atacama Large Millimeter/Submillimeter Array (ALMA) was identified as "Canada's highest priority for participation in a major ground-based observatory" in the first Canadian Long Range Plan (Pudritz et al. 2000). Following a four year design and development phase, ALMA construction began in 2003. Commissioning and Science Verification began in January 2010 and construction is currently scheduled to be completed in April 2013.

ALMA will enable transformational science in many areas. ALMA's technical specifications (large collecting area, many antennas, high resolution, flexible spectral capabilities) are driven by the three Level I science goals:

1. The ability to detect spectral line emission from CO or C II in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.

2. The ability to image the gas kinematics in protostars and in protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling the study of their physical, chemical and magnetic field structures and to detect the tidal gaps created by planets undergoing formation in the disks.

3. The ability to provide images at an angular resolution of 0.01 arcsec, and precise images at an angular resolution of 0.1 arcsec. Here the term "precise image" means being able to represent, within the noise level, the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness.

Beyond these top-level science goals, ALMA will be a powerful and flexible instrument that can be used to address a wide range of scientific questions from planetary science to cosmology. We can expect new and exciting results from ALMA on topics ranging from: planets, asteroids and comets in our own solar system; debris disks and possibly even exosolar planets around nearby stars; low and high mass star forming regions both in our own and in other nearby galaxies; the circumstellar envelopes of evolved stars in our own Galaxy and the Magellanic Clouds; detailed gas dynamics around massive black holes in nearby and distant galaxies; high-resolutions observations of the gas and dust around a wide variety of galaxies and quasars at high redshifts; and many, many more topics.

A final important goal for ALMA rests on operations philosophy rather than science: ALMA is being designed to be usable by professional astronomers whose primary technical expertise is not in radio astronomy. With fully queue-scheduled and remote observing, a Scientific Pipeline that is being designed to produce scientific quality final images, and a powerful archive to provide access to the data, ALMA will be an observatory for the entire astronomical community.

2. CONSTRUCTION

The international ALMA project has been very successful in managing the construction phase. The integration of Japan as a third major partner has brought new capabilities, including 3 additional receiver bands and the 16-antenna ALMA Compact Array which will enhance ALMA's imaging fidelity. A list of ALMA construction milestones is given in Appendix 1.

2.1. *Canadian successes and highlights*

Canadian funding for ALMA construction has come from NRC and a CFI grant to the University of Calgary (see Tables 1 and 2). Two of our main construction contributions have been completed (the site fee and software development). Canada's most visible and largest single task in ALMA construction is the design, development, and construction of the Band 3 (84–116 GHz or 3 mm) receivers. In addition to being used for routine science observations, they will also be important receivers for the initial commissioning of ALMA and for phase calibration of ALMA's highest frequency receivers. In addition, our participation in ALMA construction was also predicated upon the in-kind delivery of the new correlator for the EVLA as part of the North American Program for Radio Astronomy (NAPRA). This correlator has been built by the HIA Penticton group at a cost of roughly $20M and their outstanding job is critical to ensuring that the EVLA will similarly revolutionize science in the centimetre regime.

The Band 3 team at HIA used the design and development and pre-production phases to identify a number of components of the receivers that could be out-sourced to Canadian industry, as well as to validate the design and the automatic test equipment. During the production run, which began March 2008, HIA is responsible for the final integration and testing, to ensure the highest quality receivers are passed on to the ALMA project. A total of 18 receiver cartridges have been delivered to the ALMA project and the first two cartridges have been accepted. We are currently on schedule to deliver the 73 Band 3 receivers by the end of February 2012, on time and to the strict ALMA specifications. The team at HIA has done an outstanding job with the Band 3 receiver project.

Agreements between NRC and NSF give Canada a representative on the ALMA Board and the ALMA Science Advisory Committee (ASAC); we have also had representatives from time to time on the ALMA Management Advisory Committee and on ad hoc committees (such as the search committee for a new ALMA director). Canadians are also employed in key positions within the ALMA project (Table 3). Chris Wilson (McMaster) has served as the Canadian ALMA Project Scientist since 1999 and has benefited from advice and guidance from the Canadian ALMA Science Advisory Committee (CASAC) since 2001 (Table 4). The CASAC has played a key role in disseminating information on ALMA to the Canadian community, including organizing community information sessions and invited talks at CASCA meetings and ALMA-focused summer schools (Appendix 2).

One major and unique initiative that has been undertaken by Canadian astronomers interested in ALMA has been the development of an "ALMA Primer". This 36-page document, produced by NRC-HIA and the University of Calgary, contains an introduction to ALMA, useful information about ALMA, and sample science cases including observing parameters needed to carry out the sample projects. The Primer is available on-line at **http://almatelescope.ca/ALMAPrimer.pdf** and has been drawing attention and praise from other parts of the ALMA project, including the ALMA Board. The Primer will be an extremely valuable resource in preparing the community to use ALMA in the next few years.

2.2. *Challenges*

In 2005, the international ALMA project faced considerable financial difficulty: the total construction costs had become better understood, but had risen substantially. Even with a significant increase in budget, it was clear that some descoping would be required. ALMA made extremely good use of the ALMA Science Advisory Committee to bring ALMA back into budget without a significant compromise to its scientific capabilities. Although this process resulted in a reduction in the number of antennas in the main array from 64 to 50, the international scientific consensus is that ALMA, as built, will produce transformational science.

In Canada, because our ALMA construction contracts are specified in deliverables rather than dollars, we have been largely shielded from these higher construction costs. On the other hand, we are responsible for any increased costs inherent in delivering the Band 3 receivers and the EVLA correlator. In terms of construction deliverables, it has been and will continue to be a challenge to meet the very demanding delivery schedule for the Band 3 receiver cartridges. No problems are foreseen at this time, but such a tight schedule is very sensitive to perturbations such as equipment failure or illness of key personnel. The Band 3 cartridges are not currently on the ALMA critical path.

On a more minor note, we were hopeful that Canada's involvement in software development would enable us to assume a leadership role in some component or subcomponent of ALMA software. Although this issue has been highlighted for several years, we have not so far been able to leverage successfully our software work in this manner. One result is that Canada's contribution to software has had a less visible role in Canada than the Band 3 receivers.

3. THE NEXT DECADE FOR ALMA

The next decade will be very exciting for ALMA, one that will see the first scientific observations, the completion of construction, and more than five years of routine operations. It will also see the start of ALMA development to enhance the scientific capabilities of ALMA further. In the short term, the first major milestone will be the start of scientific commissioning for ALMA, which will begin early in 2010. The next major milestone will be the first call for proposals for Early Science, which is planned for January 2011. Early Science observing is planned to start in the second half of 2011 using at least 16 antennas each equipped with at least 3 receiver bands. The current ALMA schedule shows the end of construction in April 2013, which is just 4 months later than the 2005 rebaselined schedule.

By 2020, we can expect that ALMA will have made a large number of revolutionary observations. The level I science goals of imaging Milky Way-type galaxies at $z = 3$, imaging the physical, chemical, and dynamical properties of protoplanetary disks, and high-fidelity imaging at $0.1''$ resolution will have been achieved for a large number of sources. The rapid imaging power of ALMA will also permit large, systematic studies for the wide variety of topics described in §1, which will allow astronomers to study not just the exceptional but also the more typical disks, stars, and galaxies. In the longer term, Canadians will also have access to data from the JWST, the EVLA, and hopefully also the TMT. With a small and well-connected community, we are in a good position to exploit synergies between these different telescopes.

3.1. *Current issues for ALMA and Canada*

Over the next few years, the important issues for Canadian participation in ALMA are: (1) to secure the funding necessary to complete our Band 3 construction commitments; (2) to secure complete Canadian funding for ALMA operations; (3) to identify a visible role for Canada in ALMA operations; (4) to prepare the Canadian community to be effective ALMA users, both in Early Science and in full operations; and (5) to position ourselves to lead or play a major role in one or more ALMA development projects.

There are two critical funding issues in the near future that Canada must face regarding ALMA: completing the construction funding and securing operations funding. Although the community was successful in obtaining the first 5 years of funding for the LRP, the second 5 years of funding never achieved the status of an item in the federal budget. Thus, ALMA construction has been funded year to year out of NRC/HIA funds. It is critical that the final construction funds be available to complete our Band 3 commitment.

Regarding operations, funding for ALMA operations began in 2007 and is increasing every year. This operations funding is both required by the international ALMA project and critical to ensure that high quality scientific support for Canadians will be available during Early Science in 2011. Annual funding for Canada's contribution to ALMA operations has not yet been secured. This is an urgent issue, as we are responsible for 7.25% of the North American share of ALMA operations (2.72% of the total). The ALMA operations budget is ramping up swiftly and is expected to reach steady state by 2013.

Broad agreement has been reached with NRAO concerning the initial roles that Canada will play in ALMA operations (Table 5). However, it is very important that Canada have a visible role in ALMA operations, one that includes intellectual value to both the community and HIA, something that we can point to as a uniquely Canadian contribution to ALMA operations. It is critical that Canada work with our North American partners to identify such an operations role.

The CASAC has begun a series of initiatives to help prepare the Canadian astronomical community to be effective ALMA users (see Appendix 2). The first opportunity will come with the Early Science call for proposals early in 2011. In the initial years of ALMA operations, there will be one call for proposals per year. ALMA currently plans to have a single Time Allocation Committee, a mode of operation that has been consistently endorsed by the CASAC. There is no upper (or lower) limit to the amount of time that can be awarded to Canadian PIs. How well this process works in enabling access by Canadians to ALMA observing time should be monitored, especially in the first few years of ALMA operations.

Finally, it is important for Canada to be involved in a major or leading role in one or more ALMA development projects. The current concept for ALMA development is that groups will compete for funds to complete a project that has been identified as a high priority. To succeed in such competitions requires years of preparatory R&D work. One potential project in which Canada could take the lead is the Band 1 (31–45 GHz) receivers; other examples include focal plane array feeds, software development, and a next generation correlator.

The Band 1 receivers were identified as one of the 6 highest priority receiver bands for ALMA in the October 2001 ASAC report. As the longest wavelength receivers for ALMA, the Band 1 receivers allow access to a new suite of scientific problems, ranging from the Sunyaev-Zel'dovich effect in galaxy clusters to thermal radio continuum emission in protoplanetary disks. There has already been two years of scientific and technical development for the Band 1 project carried out at HIA and Canadian universities. The technical requirements of the Band 1 receivers fall naturally within the range of expertise of the HIA receiver group. The CASAC considers that this is a very high priority project for Canada during ALMA's post-construction development. HIA hosted a scientific and technical meeting in fall 2008 which included participants from Chile and Taiwan, and the science case for Band 1 has been written up by Johnstone et al. (2009); a separate LRP white paper gives more details (Claude & Di Francesco 2010). The Band 1 case illustrates that it is important that funding be available for pre-proposal development, to hold meetings and form collaborations, etc.

3.2. *How will Canadians judge the success of ALMA?*

An interesting question to consider at this time is how we are likely to judge the success of Canada's participation in ALMA by the time of the next LRP review in 2020. In other words, what accomplishments by ALMA and the Canadian user community would lead to our community viewing our participation in ALMA as a success? There are many possible answers to this question, but success would likely involve:

1. significant numbers of Canadian first author papers are based on ALMA data or theoretical interpretations of ALMA data
2. Canadian first author papers based on ALMA data or theoretical interpretations of ALMA data have a high impact
3. Canadians are playing important roles in some of the very highest profile ALMA papers coming from large international teams
4. significant numbers of Canadian astronomers who do not have radio astronomy as their primary background are involved in ALMA science, either as a primary user of data or as a significant collaborator
5. Canadian graduate students are participating or leading ALMA papers and using ALMA data in their theses
6. the Band 3 receivers are delivered on time, meet or exceed ALMA specifications, and are being used for good science by international ALMA community
7. Canada is leading or playing a major role in an interesting ALMA development project such as the Band 1 receivers
8. Canadians are playing a leadership role in some aspect of ALMA operations in North America or internationally

If we enter the 2020 LRP review with all of these goals achieved, then there will be a good chance that the Canadian astronomical community will be satisfied with our participation in ALMA and will view it as a success.

Acknowledgements: This report has been approved by the Canadian ALMA Science Advisory Committee: Doug Johnstone, Brenda Matthews, Erik Rosolowsky, Marcin Sawicki, Douglas Scott, Tracy Webb, and Chris Wilson. I would also like to acknowledge valuable comments and input from Jim Hesser, Gerald Schieven, Greg Fahlman (HIA) and Carol Lonsdale (NRAO).

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Johnstone et al., 2009, "The Science Case for Building a Band 1 Receiver for ALMA", arXiv:0911.2339
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APPENDIX

A1. ALMA CONSTRUCTION MILESTONES

- NSF and ESO sign agreement to start ALMA construction Feb 2003
- ALMA groundbreaking November 2003
- Japan signs agreement to join ALMA bringing new capabilities (3 receiver bands and the Atacama Compact Array) 2005
- NSF contract for 25 antennas signed 2005
- (Canada) first prototype Band 3 receiver completed 2005
- ESO contract for 25 antennas signed 2006
- (Canada) after a successful pre-production run of 8 receiver cartridges, the Band 3 production run began March 2008
- first quadrant of correlator installed at high site Q3 2008
- first 12m antenna accepted from Japanese contract January 2009
- first antenna accepted from NSF contract February 2009
- first fringes at the Operations Support Facility (OSF, 3000 m) April 2009
- first antenna to the Array Operation Site (AOS, 5000 m) September 2009
- (Canada) construction funding under the CFI contract to the University of Calgary was completed fall 2009
- (Canada) first Canadian "astronomer on duty" in Chile (part of our operations contributions) November 2009
- A major milestone was reached in December 2009 with the achievement of phase closure between three ALMA antennas at the ALMA high site. Band 3 receivers played a critical role in achieving this milestone.

A2. PREPARING THE CANADIAN COMMUNITY FOR ALMA

The first ALMA-related summer school was the the successful "Submillimetre Observing Techniques" workshop held in Victoria in August 2006. This summer school had over 50 participants and ALMA was a major focus.

The first Canadian ALMA community workshop was held at McMaster 1–3 June 2009. This workshop focused on teaching participants to do data reduction with the new CASA software as well as providing a slimmed-down introduction to the basics of radio astronomy and interferometry. The workshop was attended by 55 people, including 30 graduate students, 6 postdocs, and 10 invited speakers. Participants were mostly drawn from Canadian institutions but we did have people from as far afield as the U.K. and Taiwan in attendance. We also had a very broad range of backgrounds among our participants, with many people with little or no previous exposure to submillimeter radio astronomy, but also a few interferometry experts who were interested in learning more about CASA. We received very positive feedback from the workshop participants. They found the lectures very useful and particularly appreciated the hands-on work with CASA on the third day. The presentations and scripts used on the demo are all available on the web at

`http://www.almatelescope.ca/Workshop/Schedule.html`

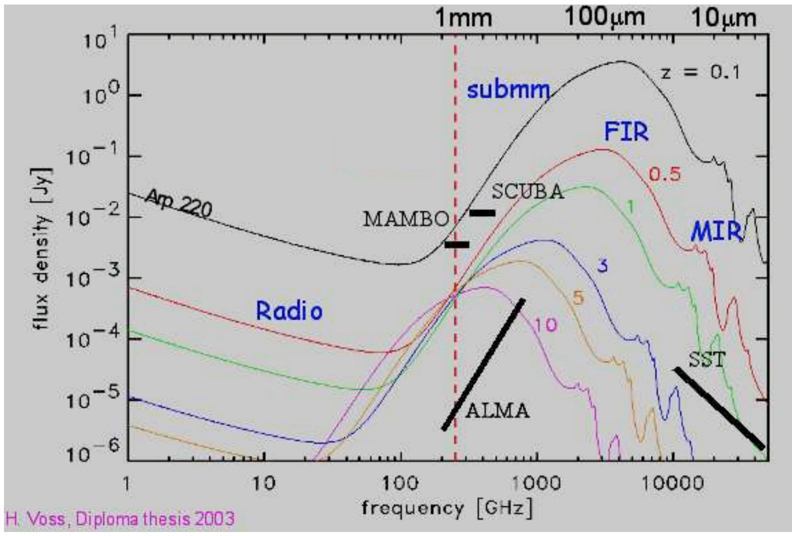

FIG. 1.— Redshifted spectral energy distribution of an ultraluminous infrared galaxy at various redshifts showing the effect of the negative K correction at submillimeter wavelengths. Figure from Bertoldi & Voss (H. Voss, Diploma thesis 2003).

and are a useful resource both for the workshop participants and for others who were not able to attend. Some of this material will be used in a similar community workshop in Taiwan in March 2010.

CASA will be especially important in Early Science, as the ALMA Pipeline will not be offered to the community for at least a year after the start of Early Science. The ALMA Primer is a great introduction to ALMA, with specific science examples that can help a new user tune their own science project.

In the near future, there will be an ALMA community information session held at the CASCA meeting in Halifax in May 2010. This 1.5 hour session will provide an overview and introduction to the most important ALMA capabilities in Early Science. There will also be a more hands-on demonstration of the Observing Tool towards the end of the CASCA meeting; ALMA observers will need to use this tool for Phase I and Phase II proposal preparation. The CASAC will also be considering whether there are other forums and events in Canada in 2010 at which possible ALMA Early Science projects could be discussed and co-ordinated. One option would be to offer "Preparing for ALMA" as a special topics course for graduate students at some Canadian universities; such a course is currently being offered at the University of Virginia by Dr. Kelsey Johnson.

Table 1
Agreed Canadian construction funding for ALMA (Y2K $US)

62 Cartridges for Band 3	$13.70M
Secondment of Dr. Charles Cunningham	$1.25M
ALMA Software	$1.20M
ALMA Archive	$0.25M
Cash payment for Chilean Site Civil Works	$3.60M
Total	**$20.00M**

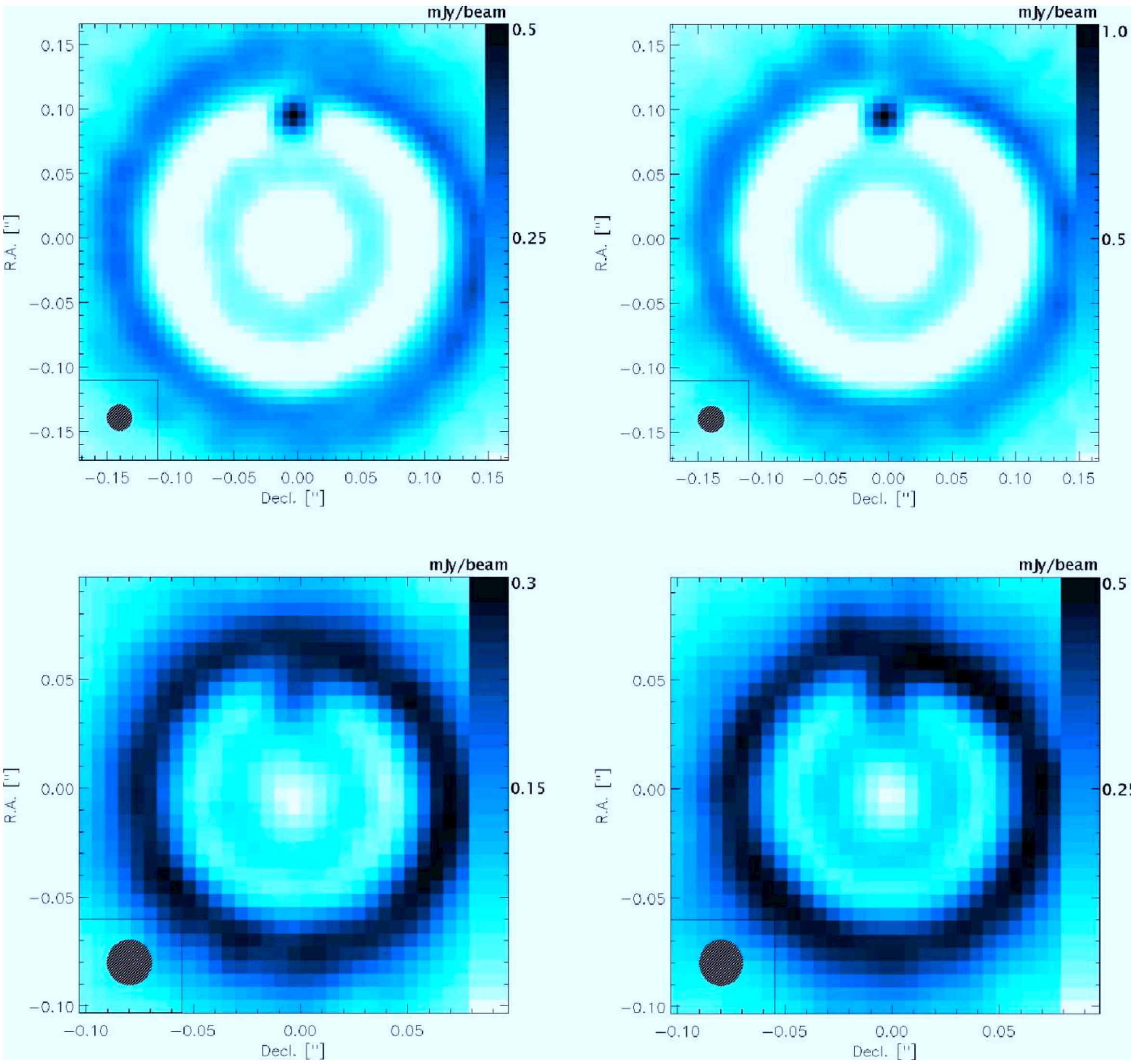

Fig. 2.— Simulation of ALMA observations of a disk with an embedded planet (Wolf & D'Angelo 2005). The left images show a Jupiter mass planet around a 0.5 $M_{\odot}$ star, while the right images show a 5 M_J planet around a 2.5 $M_{\odot}$ star, each at an orbital radius of 5 AU. The top images are for a distance of 50 pc and the bottom for a distance of 100 pc.

FIG. 3.— (left) Picture of first antenna on its way up to the high site. (right) Three ALMA antennas at the high site, where phase closure was achieved in December 2009. Picture credits ALMA (ESO/NAOJ/NRAO.

Table 2
CFI grant to University of Calgary for ALMA Construction
Actual expenditures in Canadian real-year dollars at the end of the grant
This funding is included in the summary in Table 1

Site Access Fee	$5.8M
Software development	$2.1 M
Total CFI funding (2002 $Cdn)	$7.9M

Table 3
Canadians in the international ALMA project

Charles Cunningham	Head of North American Front End integration
Rick Murowinski	ALMA Project Engineer, Joint ALMA Office, Chile
Lewis Knee	Head of Commissioning and Science Verification, ALMA, Chile
Pam Klaassen	ALMA Postdoc (ESO)
Rachel Friesen	ALMA Postdoc (NRAO)

Table 4
Canadian ALMA Science Advisory Committee (CASAC)

Current members	Past members	ex-officio
Doug Johnstone	Pierre Bastien	*Canadian ALMA Board member:*
Brenda Matthews	Stephane Courteau	Jim Hesser
Erik Rosolowsky	James di Francesco	*Canadian ALMA Project Manager:*
Marcin Sawicki	Michel Fich	Lorne Avery
Douglas Scott	Peter Martin	Lewis Knee
Tracy Webb	David Naylor	James di Francesco
Chris Wilson	Robin Phillips	Gerald Schieven
	Rene Plume	
	Chris Pritchet	
	Jean-Rene Roy	
	Ernie Seaquist	

Table 5
Canada's operation contributions for ALMA
Annual costs are estimated for 2014 in $CDN

Contribution	Estimated cost per year
Cash for on-site ALMA operations in Chile	$2.5M
In-kind contributions to the ALMA Regional Center	$0.9M

Nature of in-kind contributions
support of scientific users
"Astronomer on Duty" turno shifts in Chile
technical support of Band 3 receivers