James Clerk Maxwell Telescope (JCMT) and SCUBA-2

Submission to the Long Range Plan 2010 (February 2010)

Executive Summary

This paper provides a summary of the current state of the JCMT as well as its past, and current achievements and priorities. This summary shows that the Canadian community can efficiently use this telescope. The JCMT Board authorized the use of 55% of the telescope's observing time with its new suite of panoramic detectors to a set of far-ranging internationally approved Legacy Surveys over a period of 2-5 years. SCUBA-2 is a key element of the surveys where it is demonstrated that its science is essential to many varied fields of research. SCUBA-2 is working and the gathering of photons is imminent, therefore we recommend that the LRP 2010 panel support the use of SCUBA-2 and its ancillary instruments on the JCMT by Canadian astronomers and give a strong priority to the continuation of the Canadian partnership in the JCMT until 2015 so that the Legacy Surveys and any other forefront science are brought to fruition.

1. Introduction

The JCMT and its community of users have now reached a critical juncture. The facility may close in two years while the benefits of a state-of-the-art and un-paralleled for the foreseeable future continuum instrument (SCUBA-2) will not have been fully harvested.

The JCMT is, by any objective measure, the world's most productive submillimetre observatory and a major success story that can be attributed to the following factors:

- its location: Mauna Kea is one of the best submillimetre observing sites in the world, and certainly the very best in the northern hemisphere;
- its size: the JCMT is the largest single-dish submillimetre telescope in the world (15m), and has an active programme of surface control to maintain its accuracy;
- its instrumentation: the JCMT has had an aggressive instrumentation programme to produce leading-edge instruments with unique capabilities. SCUBA, one of the most successful astronomical instruments ever built, was the leading example of this;
- a comprehensive suite of software tools to optimise the observing programme and enhance completion of the highest-ranked projects;
- strong liaison with our ambitious user base. Astronomers go to the telescope for observing thus giving significant benefits to the facility; and
- an array of talented and dedicated staff.

The telescope is owned by the UK and is operated as a partnership between the UK (55%), Canada (25%) and the Netherlands (20%). The three funding agencies have agreed to operate the telescope under the terms of the present agreement until at least mid-2012.

The JCMT was the subject of a comprehensive, independent review in 2005 by a panel chaired by Professor Martin Harwit (Cornell). The Harwit report provided strong and enthusiastic support for the continued operation of the JCMT and for the then-planned legacy survey programme to exploit the unprecedented capabilities of the new instruments HARP/ACSIS and SCUBA-2. Followed then a JCMT Board decision to provide 55% of the observing time for the completion of the legacy surveys. The Harwit report fed into the PPARC Programmatic Review of 2005/06, which was in turn followed by the STFC Programmatic Review of 2007/08. Both reviews placed the JCMT with SCUBA-2 in the highest-priority category, confirming its status as a "must-do" project for the UK.

This document demonstrates (1) the uniqueness and complementarity of the JCMT compared to other observatories emphasizing the utmost importance of SCUBA-2 for its giving access to transformational science, (2) the strength of the Canadian community support, and (3) the scientific importance of the legacy surveys. The conclusion provides a set of recommendations that urgently need to be implemented.

2. Current Instrumentation

2.1. Strategy

The observatory is in the midst of a profound transformation. Driven by the scientific requirement for statistically-significant sample sizes, nearly the entire set of instruments is being replaced or upgraded. The third-generation instrumentation suite is optimised for wide-field submillimetre mapping in both spectral line and continuum modes. The spectroscopic component of the transformation has been completed with the release of the new instruments HARP and ACSIS; the continuum component of the transformation is near at hand, with the SCUBA-2 instrument scheduled for early release to the community in mid-February. Once this process is complete in mid-2010, the JCMT will become the fastest submillimetre mapping instrument ever built and will enter a phase of routine observations in which the majority of telescope time will be given to the JCMT Legacy Survey (about which more in §4.3).

2.2. Spectroscopic Instrumentation

The JCMT's current suite of common-user heterodyne receivers is listed in Table 1. HARP is the world's first array receiver in the 345-GHz atmospheric window, and it is currently the observatory's workhorse instrument. RxWD is the high-frequency receiver. It was recently upgraded and according to one recent observer is the most sensitive receiver in the world in the 690-GHz band.

Table 1

Receiver	Spectral Range (GHz)	Array Format	Channels per Pixel	Sideband Configuration
RxA3	211–272	1	1	Dual
HARP	325–375	4×4	1	Single
RxWD	630–710	1	2	Single

2.3. Continuuum Instrumentation

The transformation of the JCMT's continuum capability includes the replacement of SCUBA, the highly successful instrument which provided the partner countries with undisputed world leadership in submillimetre astronomy, with its successor SCUBA-2. SCUBA-2 was designed to deliver a mapping speed up to 1000 times faster than the original SCUBA, thereby opening entirely new paradigms in submillimetre astronomy. The JCMT Legacy Survey, which will capitalise on this unique capability, is described below (§4.3).

SCUBA-2 will simultaneously observe in two spectral bands, 450 and 850 microns. The focal plane in each waveband is covered by four detector arrays providing more than 5000 CCD-like pixels and giving a field of view larger than 50 arcmin^2. SCUBA-2 is a research project in itself. No one has ever built such a camera and it utilizes several brand-new technologies. Building SCUBA-2 and then understanding its operation in sufficient detail to take full advantage of it was and still is a challenging research. Despite the disappointing length of time it took to bring SCUBA-2 into operation there is no doubt that it will very soon bring the promised great science that everyone expects from it. There is every reason to expect that the full instrument will perform close to specification once it is delivered to the JCMT community at large. In order to prove this assertion, the JCMT Board has authorised a fast-track instrument commissioning programme. Two of the eight science-grade arrays have been delivered (one for each waveband) and the instrument is, at the time of writing, on the telescope and will be released to the community for shared-risk observations by mid-February. Figure 1 is the beautiful proof that SCUBA-2 is in working condition. These observations of the Orion molecular cloud were taken with only one array in weather conditions which were not as good as the compared SCUBA map. Therefore with only one array that can still be improved, the mapping speed of SCUBA-2 is already at least 100 times faster than SCUBA.

Finally, the JCMT will also be taking delivery later in 2010 of two ancillary instruments which will operate in conjunction with SCUBA-2: a polarimeter (POL-2) and a Fourier transform spectrometer (FTS-2). These ancillary instruments are being built in Canadian university laboratories using Canadian resources ($12.3 M CDN in CFI funds), and they will bring exciting new capabilities to the JCMT beyond that offered by SCUBA-2 alone: the polarimeter will provide magnetic field information which is crucial for star-formation studies, and the spectrometer will provide both dust emission spectral indices and an alternative handle on line contamination of photometric data. The combination of SCUBA-2 and its ancillary instruments will offer scientific capabilities unrivalled by any observatory in the world.

2.4. Submillimetre interferometry

The extended Submillimeter Array (eSMA) project is a collaboration between the JCMT, SMA and CSO to join all three observatories into a single interferometric array with nearly twice the collecting area of the SMA alone and an increased resolution resulting from its longer baselines. The MoU between the SMA and JCMT specifies a pilot programme of 6 weeks of eSMA observing in the 345-GHz window, spread over a year, once the commissioning has been completed. This and the subsequent operation of the eSMA will give the JCMT communities access to a submillimetre interferometer one year before the early science operations of ALMA in c.2011/12. At the time of writing, commissioning of the system is very nearly complete. Two papers have already been published, and more are in preparation, based on science demonstration data already obtained.

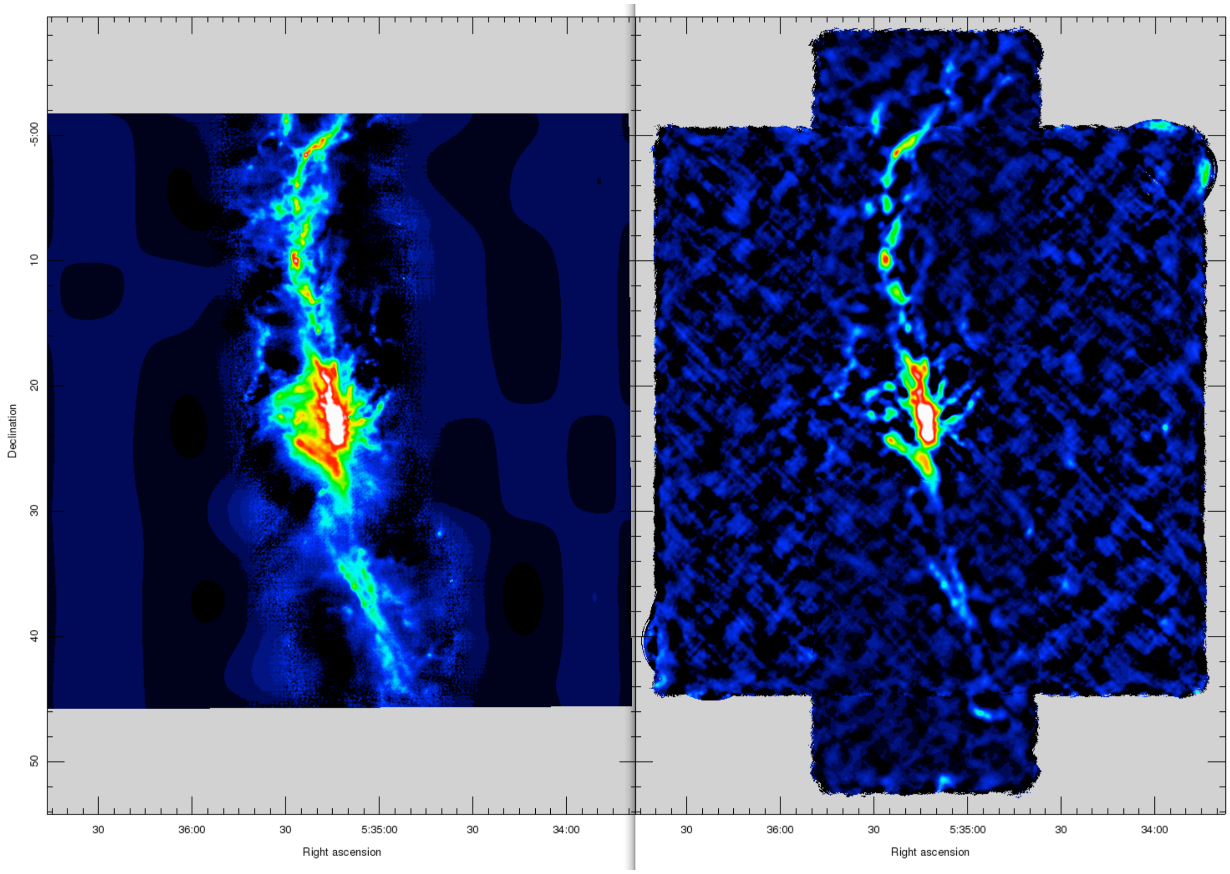

Figure 1. Comparison of SCUBA (left panel) and SCUBA-2 (right panel) observations of the Orion Molecular Cloud 1. Both images have the same spatial and flux scales. The SCUBA image took two full nights to obtain while the SCUBA-2 image took about 50 minutes. The image size is 0.7 x 1 degree. The rms noise of the SCUBA-2 map is 20-30 mJy.

3. Demand and Productivity (**a busy reader can move ahead to 4.0**)

3.1. Subscription

The Canadian subscription rate is defined as follows:

$$\text{Subscription} = \frac{\text{Time requested}}{\text{Time available}}$$

where the time requested is the sum of the time requests of all proposals received, and the time available is the total amount of time in the semester, less any planned engineering time, Director's discretionary time, Guaranteed Time for instrument teams, time committed to the JCMT Legacy Survey, and time given to other partners (UK, Netherlands, UH). No account is taken in this algorithm of likely weather losses.

With this definition, the Canadian subscription rate over time is provided in Figure 2. The slightly lower subscription rate in the period before 2005 has its origin in the SCUBA instrument which was in ill health throughout 2004, leading to its eventual retirement in 2005. During the entire period covered by Figure 2 the Canadian demand on the telescope was higher than for the UK and remained so to this day. The large fluctuations in demand since 2005 reflect the large amounts of telescope time top-sliced for the commissioning of new instrumentation. Finally, note that there was no semester 06A, as the JCMT was closed for six months for the construction of telescope infrastructure to support SCUBA-2.

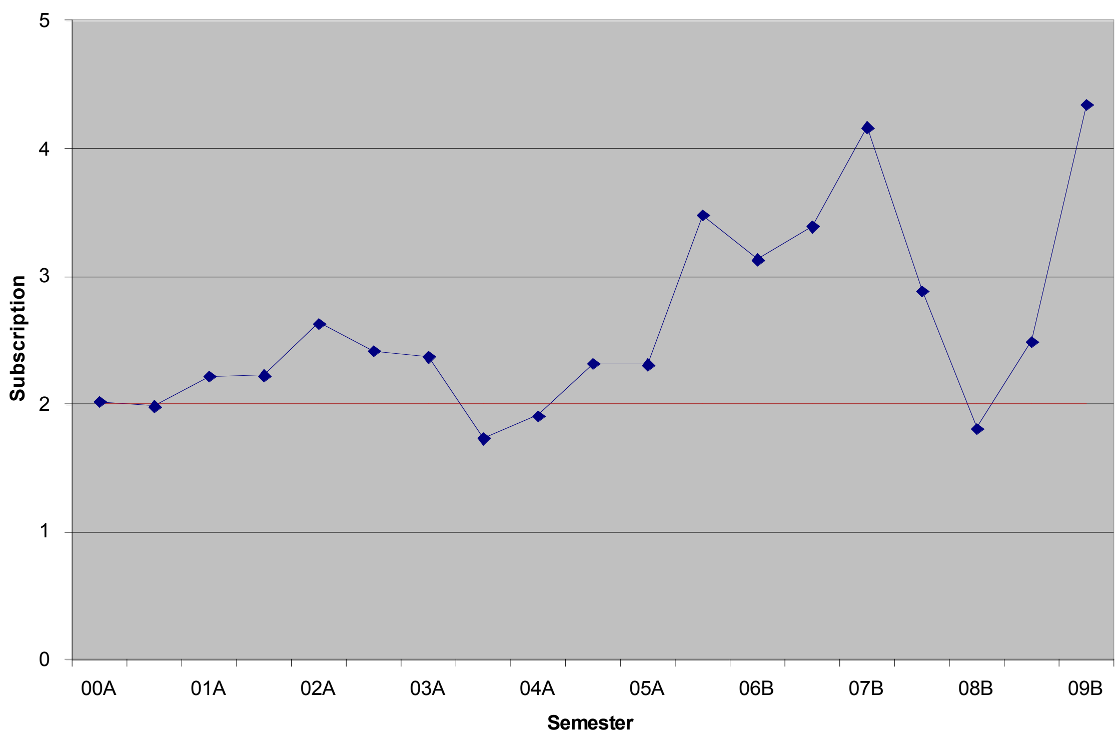

Figure 2 *JCMT Canadian subscription rate since semester 00A.*

Another metric of demand for the JCMT is the enthusiastic community response to the opportunity to develop a legacy survey programme. As described in §4.3, the initial demand amounted to 9 years of telescope time, exceeding the time available by more than a factor of 5.

3.2. Refereed Papers

The productivity of the facility is most easily characterised by the publication count, i.e., the number of papers published in major journals each year based on JCMT data. The historical record of this metric is presented in Figure 3.

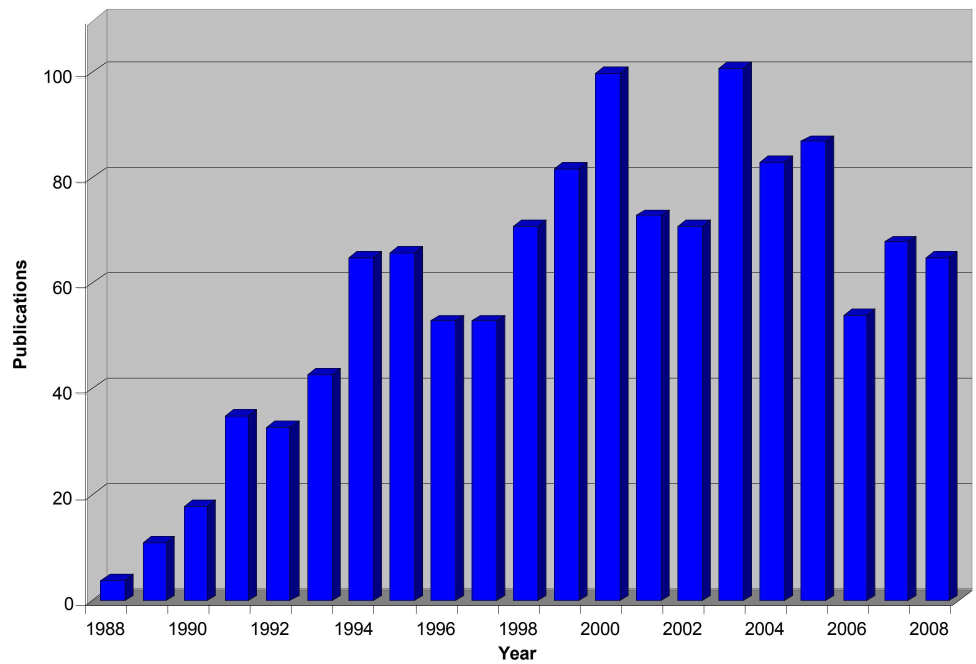

Figure 3: *Historical record of publications based on JCMT data.*

The record of papers published by instrument is provided in Table 2. Papers which used more than one instrument are counted once for each instrument. The line labelled "total" therefore includes duplicates; the line labelled "actual" represents the real number of papers published each year.

Table 2

	2004	2005	2006	2007	2008
SCUBA	66	62	39	35	32
SCUBA-2	0	0	0	5	0
RxA	9	13	4	12	17
RxB	9	19	6	22	19
HARP	0	0	0	0	6
RxW	1	11	3	2	2
Visiting & other	1	5	2	5	4
TOTAL	**86**	**110**	**54**	**81**	**80**

The record of papers published by science area is provided in Table 3.

Table 3

	2004	2005	2006	2007	2008
Cosmology	23	19	9	10	14
Extragalactic	12	17	7	11	9
ISM / star formation	35	34	29	34	28
Stellar	12	11	8	6	6
Solar System	3	3	0	1	5
Instrumentation	1	3	1	6	3
TOTAL	**85**	**87**	**54**	**68**	**65**

Another productivity metric is the cost per paper, i.e., the annual cost of operating the facility (c. \$3.3M/yr) divided by the number of papers published each year. For the JCMT in 2008, this metric was \$51k/paper. This value compares extremely favourably with other facilities.

3.4. Comparative Studies

The metrics described above are specific to the JCMT, and although they indicate temporal trends in demand and productivity, they do not by themselves provide an objective comparison

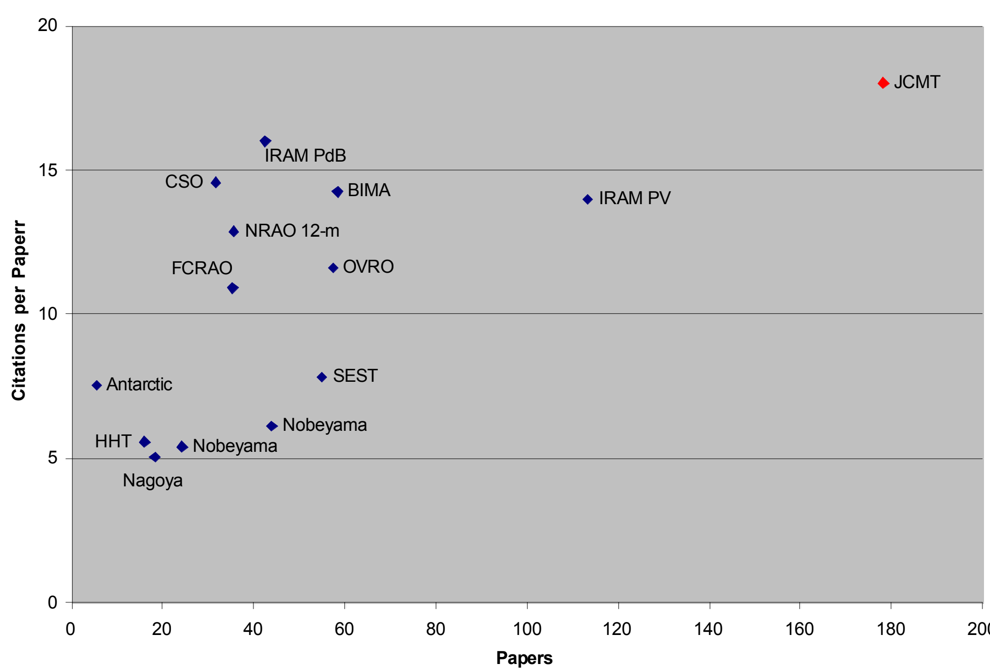

Figure 4: *Productivity and impact metrics for submm/mm observatories. The JCMT leads the field by a wide margin.*

against other observatories. Such comparisons appear in the literature from time to time. A compilation of citations to high-impact papers in 1999, for example, only two years after SCUBA was commissioned, ranked SCUBA second only to the Hubble Space Telescope, beating all other ground and space facilities, let alone any single instruments. More recently, a survey by Trimble & Ceja (Astron. Nachr. **329**, 632, 2008) of publications and citations over specific time periods for a large number of observatories placed the JCMT first in the world amongst submillimetre and millimetre telescopes according to all three metrics they used: number of papers, number of citations, and citations per paper (Figure 4). Studies such as these have specific methodologies and the results require careful interpretation, but it is rewarding nonetheless to see the JCMT ranked at the top of its class by a very wide margin (See Annex 1).

4. Current context and near Future

4.1. Context

Again, the JCMT is in a dire situation. Its tripartite agreement between the partner countries was supposed to end in 2009. The delays in bringing SCUBA-2 to the telescope and the promise of its revolutionary science convinced the funding agencies to extend the agreement to Spring 2012. Further delays makes this deadline still short of the full scientific exploitation of SCUBA-2. Meanwhile NRC is facing the ramp-up of funding for ALMA since there is a lack of a line item in the federal budget for ALMA. A further extension of the tripartite agreement with Canada as a partner is therefore very uncertain (see the Autumn 2009 memo sent out by Greg Fahlman).

The spectroscopic capability of the JCMT will face competition from ALMA, once that facility becomes operational. On the other hand, the continuum capability of the JCMT, represented by SCUBA-2, has no foreseeable competition even in the ALMA era. This is such a technically ambitious and revolutionary instrument that no other submillimetre observatory has built, or is planning to build, anything comparable. The nearest competitor, ARTEMIS on APEX, will have a mapping speed 10 times lower at best. It is therefore clear that, until a similar camera is put on a larger submillimetre dish, the JCMT, equipped with SCUBA-2, will be without peer. The only potential competitor to SCUBA-2 is the Herschel space telescope whose last observing waveband is 500 microns. Since SCUBA-2 is attached to a larger telescope, its spatial resolution is 5 times better at 450 microns. Since SCUBA-2 can observe at both 450 and 850 microns, it provides an extension to the sampling of the spectral energy distribution for any type of cold objects. This extension is very important to derive dust grain properties (size, temperature, composition…). These two assets make SCUBA-2 the perfect complementary facility for any Herschel science. Annex 2 contains a figure extracted from work done by Ed Chapin where extragalactic images from BLAST, Spire and SCUBA-2 are compared. This image clearly states that if you want to move past noticing that the cosmic infrared background comes from galaxies and ask which galaxies, what types and at what redshift, the angular resolution of the JCMT is needed.

4.2. Strategy

The top priority once SCUBA-2 is commissioned is to focus on harvesting science results from the JCMT Legacy Survey (§4.3) to capitalise on the investment which has been made in the new suite of instruments (c. $33M CDN). Neither RxA3 nor RxWD are expected to be competitive beyond 2012. Similarly, the rationale for the interferometry capability provided by the eSMA is considerably weakened once ALMA commences early science in 2011/12.

4.3. JCMT Legacy Survey

A comprehensive legacy survey programme was approved by the JCMT Board in July 2005. This was the culmination of a community-based process that began with a call for ideas and proceeded via Letters of Intent and a very successful community meeting in Leiden to the submission of proposals and final Board approval. The Letters of Intent had indicated a likely total request that exceeded the time available by more than 500%, supported by over 200 active astronomers in the partner countries (60 of them are Canadians). Seven proposals were received, requesting four of the JCMT instruments (HARP, SCUBA-2, FTS-2, POL-2) and covering a wide range of scientific areas: three dedicated to the study of star formation in nearby molecular clouds and the Galactic plane; one to conduct an unbiased search for debris discs around 500 nearby stars; one to study several hundred nearby galaxies; a deep cosmology survey, building on the breakthrough SCUBA surveys; and an all-sky survey, making use of poorer weather conditions to produce the first-ever atlas of the submillimetre sky visible from Mauna Kea. The proposals were rigorously peer-reviewed by a panel of 10 senior international astronomers, whose reviews provided strong support for the entire survey programme.

The Board therefore approved a JCMT Legacy Survey (JLS) requiring a total of 265 nights over a two-year period. It also approved, in principle, a further 307 nights over a further three-year period, subject to review and to renewed competition, to finish the surveys.

The JLS is of the highest scientific calibre, with extraordinary quality and scope. The surveys will revolutionise our understanding of planet formation processes; they will address questions fundamental to star-formation studies, and obtain a molecular inventory of objects spanning a range of evolutionary stages and physical environments; they will produce the first large sample of local galaxies observed with good spatial resolution at submm wavelengths; the entire sky visible to JCMT will be mapped, including deep scans of the accessible Galactic Plane, placing massive star formation research onto a firm statistical basis for the first time. Last, but not least, the cosmology programme will revolutionise our understanding of galaxy formation, yielding a survey of enormous and lasting legacy value. All the surveys promise to be uniquely powerful levers for the exploitation of the growing range of public survey datasets and a springboard for future exploitation of ALMA, Herschel, LOFAR, JWST and the SKA. The knowledge gained from the JCMT Legacy Survey will have far-reaching benefits for the whole of astrophysics.

In order to ensure the long-term legacy value of the JLS, the JCMT is collaborating with the Canadian Astronomy Data Centre to create the JCMT Science Archive (JSA). This facility will provide a service for curation and distribution of raw and reduced data and publication-quality advanced data products (e.g., intensity maps, spectral data cubes, source catalogues). The JSA project was ranked second in priority behind SCUBA-2 by the Harwit review of 2005. The Archive will be fully integrated with the Virtual Observatory and in this way will ensure the legacy value of the JLS data.

Three of the seven survey projects have observational components using HARP, and these are well advanced. The bulk of the time allocated to the JLS, however, was for observations with SCUBA-2 (82% in the two-year programme). These are expected to commence in mid-2010 and the two-year programme should thus be complete in mid-2012. Based on the international reviews of the JLS proposals, and on the absence of any real competition for SCUBA-2, it is clear that there is a major science case for the continued operation of SCUBA-2 on the JCMT for several years beyond 2012.

5. Conclusion

A poll of the Canadian astronomical community spearheaded by Douglas Scott took place in late Autumn 2009. Fifty-nine CASCA members replied: (1) 77% were against ending Canada's involvement in the JCMT, (2) 72% were planning to use SCUBA-2 for their research, (3) 94% believed SCUBA-2 would provide ground-breaking science results, and (4) 70% said that the JCMT Legacy Surveys were likely to become part of their research.

Therefore,

since the JCMT is involved in forefront science (over the period 2000–06 inclusive, the average number of citations to papers in the JCMT publication list exceeded the average number of citations to ADS papers in general by a factor of 2.5.);
since the JCMT has a very strong user base in Canada, including graduate students;
since the JCMT Legacy Surveys involve an important fraction of Canadian interstellar medium researchers (60);
since the JCMT Legacy Surveys have had very strong international peer review support;
since the new panoramic instruments are providers of transformational science;
since a withdrawal from the JCMT tripartite agreement will jeopardize Canadian participation in forefront submillimetre research;

We recommend that the LRP 2010 panel support the use of SCUBA-2 and its ancillary instruments on the JCMT by Canadian astronomers and give a strong priority to the continuation of the Canadian partnership in the JCMT until 2015 so that the Legacy Surveys are brought to fruition.

Gilles Joncas,
Chair JCMT Board.

Gary Davis (Director JAC), Michel Fich (U. of Waterloo), Mark Halpern (UBC), Doug Johnstone, Brenda Mattews, Gerald Moriarty-Schieven (HIA), René Plume (U. of Calgary), Douglas Scott (UBC)

Annex 1: JCMT's Top Papers

A. Top Historical Papers

- Hughes *et al.*, "*High-redshift star formation in the Hubble Deep Field revealed by a submillimetre-wavelength survey*". Nature **394**, 241 (1998). [662 citations] This paper demonstrated the power of SCUBA as a new tool for observational cosmology. Observations of the HDF revealed the presence of 5 sources whose combined radiation accounts for almost half of the previously-unresolved background emission in this area.

- Andre *et al.*, "*Submillimeter continuum observations of Rho Ophiuchi A – The candidate protostar VLA 1623 and prestellar clumps*". ApJ **406**, 122 (1993). [559 citations] This paper reported the discovery of the youngest classification of protostar, named by the authors "Class 0".

- Smail *et al.*, "*A Deep Sub-millimeter Survey of Lensing Clusters: A New Window on Galaxy Formation and Evolution*". ApJ **490**, 5 (1997). [500 citations] This paper reports on the first deep cosmological survey conducted with SCUBA.

B. Top Recent Papers

- Chapman et al., "*A Redshift Survey of the Submillimeter Galaxy Population*". ApJ **622**, 772 (2005). [158 citations] The Keck telescope was used to measure the spectroscopic redshifts of 73 SCUBA galaxies.

- Andrews & Williams, "*Circumstellar Dust Disks in Taurus-Auriga: The Submillimeter Perspective*". ApJ **631**, 1134 (2005). [52 citations] This survey of 153 YSOs detected 61% of sources down to 10 mJy at 850 microns. Evidence is presented which shows that the submillimetre flux and mass of the disks decrease along the evolutionary sequence defined by the infrared SED.

- Crutcher et al., "*SCUBA Polarization Measurements of the Magnetic Field Strengths in the L183, L1544, and L43 Prestellar Cores*". ApJ **600**, 297 (2004). [48 citations] Using the SCUBA polarimeter, magnetic field strengths were estimated for three prestellar cores. The findings are consistent with models of star formation driven by ambipolar diffusion or turbulence.

C. Recent Major Achievement

- Doeleman, S.S. et al., "*Event –horizon-scale structure in the supermassive black hole candidate at the Galactic Centre*". Nature Letter **455**, 78 (2008). First VLBI submm observations.

Annex2: Chapin study

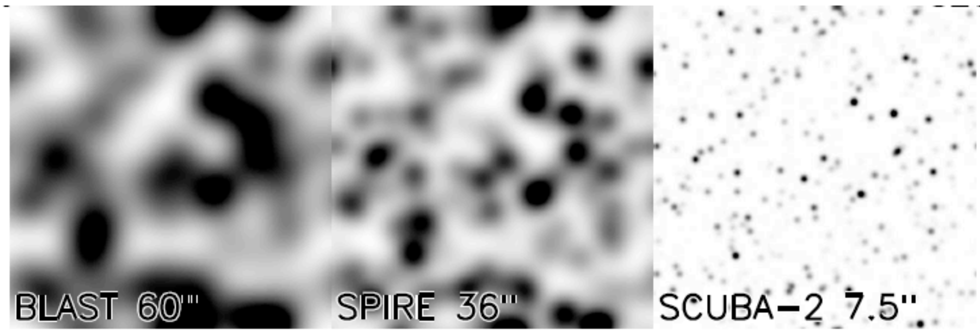

Figure 1: New predictions for our proposed 50-arcmin^2 450 μm map of the UDS/SXDF field, demonstrating the power of SCUBA2. A realisation drawn from BLAST 500 μm source counts (extracted via P(D) analysis by Patanchon et al. 2009, arXiv:0906.0981) has been used to create the three 50 arcmin^2 simulated images shown in the grey-scale panels, where the source population has been convolved with the appropriate beam sizes for BLAST, *Herschel*+SPIRE and JCMT+SCUBA2 as indicated in each panel. We aim for an rms of $\sigma_{450} \simeq 2.5$ mJy, and "expect" to detect $\simeq 30$, $> 4\,\sigma$ (i.e. $S_{450} > 10$ mJy) sources in our new SCUBA2 image.