THE SUBMILLIMETRE UNIVERSE[†]

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ABSTRACT

Submillimetre continuum radiation allows us to probe cold objects, particularly the earliest, dusty phases of star formation, high-redshift galaxies and circumstellar disks. The submillimetre window gives a unique view of the physical and dynamical conditions in the neutral and molecular interstellar medium. In the next decade a combination of wide-field surveys with single-dish telescopes and targeted follow-up with ALMA and other facilities should enable rapid progress in answering questions about the origins of planetary systems, stars and galaxies.
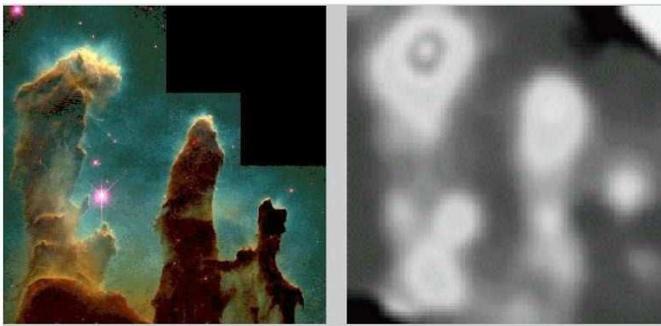
Subject headings: Submm – Universe

Fig. 1.— *Left*: Iconic optical image of the Eagle Nebula taken by the *Hubble Space Telescope*, showing the 'elephant trunk' columns protruding from the molecular cloud, illuminated by nearby young stars, but with the youngest objects buried inside. *Right*: SCUBA image at $450\,\mu$m showing thermal dust emission, unveiling the cold cores where the earliest stages of star formation can be studied [1].

Fig. 2.— Part of the 'integral-shaped filament' in Orion, imaged using the SCUBA camera on the JCMT [6].

1. THE SUBMM WINDOW

The sub-millimetre (hereafter 'submm') waveband is usually defined to stretch from $200\,\mu$m to $1\,$mm. There are strong physical reasons why this range of wavelengths is of particular astronomical interest, reasons which are partly shared with the neighbouring far-IR and mm bands. In accord with the 'Origins' theme of the 2000 Canadian Long Range Plan, the earliest stages of planet, star and galaxy formation are most directly amenable to study at submm wavelengths.

The youngest systems in the Universe tend to be shrouded in dust, which absorbs shorter wavelength radiation and re-emits at hundreds of microns (Fig. 1). So to study cold systems, including the early stages of star formation, debris disks in nearby stellar systems and high redshift star-forming galaxies, one naturally turns to submm wavelengths, where the opacity is low and thermal emission is being probed directly.

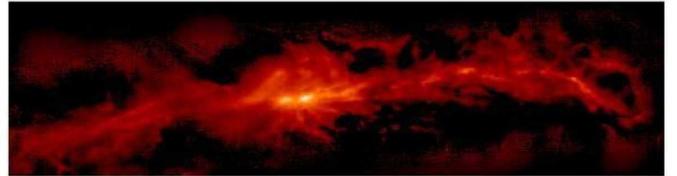In addition to continuum radiation, spectral features in

the submm are diagnostics of the detailed physical conditions within dust and gas clouds. In fact most known interstellar medium (ISM) molecules have their lowest transitions at far-IR to mm wavelengths. The rich spectrum in the sub-mm, including dominant cooling lines of the atomic and molecular components of the ISM, traces a range of excitation properties. Sub-mm spectroscopy determines density, temperature, etc. in ionized and neutral gas, as well as dust. This is the only part of the electromagnetic spectrum which provides a complete picture of all phases of ISM. And in extragalactic systems one can also learn about the hardness of the interstellar radiation field, distinguishing black hole sources in Active Galactic Nuclei (AGN) from hot young stars.

The relatively long wavelengths mean that single dish submm telescopes have beamsizes typically $\sim 10''$, which is a major limitation for probing down to the scales most relevant for understanding star formation, and also makes identification of extragalactic sources challenging. However, submm interferometers provide the kind of resolution which is routine at optical wavelengths, and indeed are able to reach below $0.1''$. However, one must appreciate that the field of view of an interferometer is determined by the size of each antenna – hence it is essentially the same as the *beamsize* of a single dish telescope. This makes it natural to use large-format array detectors on single dish telescopes for surveys, combined with follow-up observations with interferometers.

Polarization gives another dimension to submm studies, tracing magnetic fields through alignment of dust grains. Through continuum measurements, spectroscopy and polarimetry a wide range of science topics can be ex-
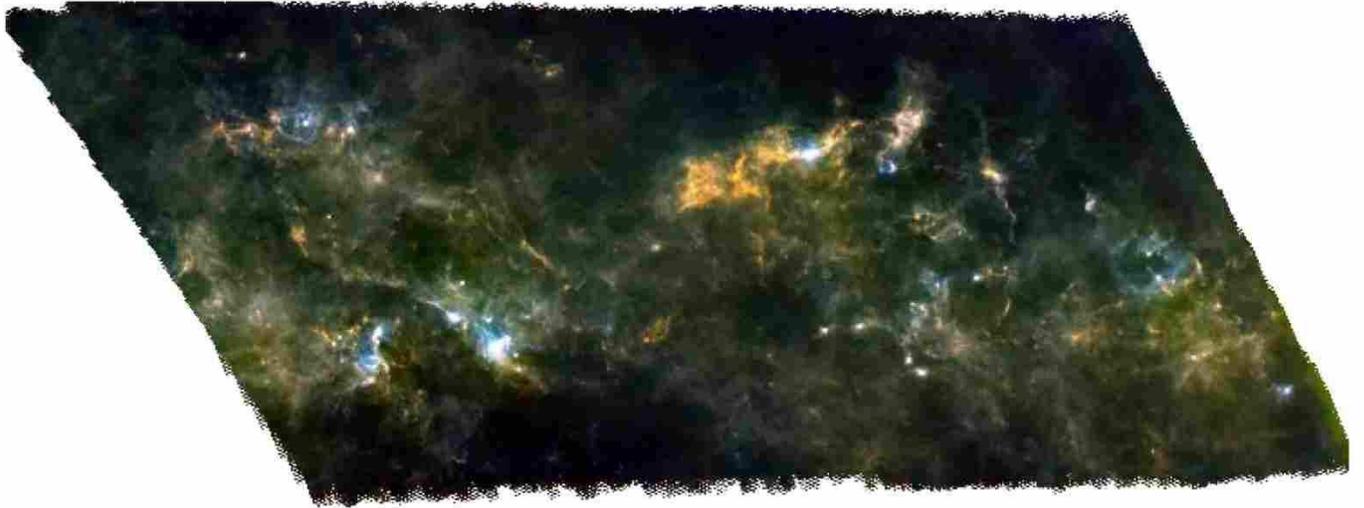
FIG. 3.— Submillimetre 3-band image of the Vela star-forming region [9]. The image covers about $50\,\mathrm{deg}^2$, and shows a wide range of morphologies associated with recent and on-going star formation. The combination of filters spanning the thermal peak for cold sources means that one can literally *see* temperature in this image – red regions are genuinely colder.

plored at submm wavelengths, including studies of planetary atmospheres, comets, Kuiper Belt objects, evolved stars and planetary nebulae. But the highest impact has come from results from extragalactic astronomy, star formation and circumstellar disks – all areas in which Canadians have made major contributions.

2. THE CANADIAN CONTEXT

In 1987 Canada joined the U.K. and the Netherlands in a partnership to run the James Clerk Maxwell Telescope (JCMT [2]). This effectively built on Canadian expertise in atomic and molecular spectroscopy (personified in Gerhard Herzberg) and radio astronomy (with telescopes at Penticton and Algonquin). Now Canadian astronomers had access to the best submm facility in the world, and they were quick to exploit it. With early instrumentation consisting of single element bolometers and heterodyne spectrometers, it was natural that relatively bright Galactic objects were the main focus of study. Canadian users of the JCMT therefore made significant contributions to our understanding of the ISM and star formation, as well as Solar System objects.

However, the arrival of the Submillimetre Common-User Bolometer Array (SCUBA) in 1996 made it routine to map fainter objects, and the submm window opened up to the extragalactic community as well. In the years around 2000 the JCMT (and SCUBA in particular) achieved citation rates which were second only to the *Hubble Space Telescope* among all astronomical facilities (see [3]). Specific Canadian contributions include the Canada-UK Deep Submillimeter Survey (e.g. [4]) and imaging of the Hubble Deep Field (e.g. [5]) and Integral-shaped Filament in Orion (Fig. 2 [6]), to focus on some of the higher impact results.

As well as observational and theoretical work, the submm has also been a fruitful waveband for developing instrumental expertise within Canada. Several hardware projects have only been possible through the existence of the instrumentation group at the Herzberg Institute of Astrophysics. But there has also been experimental development at many Canadian universities, including British Columbia, Lethbridge, McGill, Montreal, Toronto, Waterloo and Western Ontario.

A vigorous Canadian programme in studying the Cosmic Microwave Background (through rockets and balloons) also has a strong synergy with the science goals of submm instruments (see [7]). This explicitly resulted in the Balloon-borne Large-Aperture Submillimetre Telescope (BLAST), a US-led project with strong involvement from UBC and UofT. A precursor to the SPIRE instrument on the *Herschel* satellite, BLAST has had 2 successful flights, resulting in more than 20 refereed papers (e.g. [8], see Fig. 3).

Through a successful CFI grant, Canada became a partner in the development of SCUBA-2, an ambitious submm array camera using $\sim 10^4$ transition edge sensor bolometers, described in more detail in a separate paper [2]. A series of community discussions and proposals resulted in the following 7 surveys being allocated a large slice of JCMT telescope time: SCUBA-2 'All-Sky' Survey; Cosmology Legacy Survey; Nearby Galaxies Survey; JCMT Galactic Plane Survey; Gould Belt Survey; Spectral Legacy Survey; and Debris Disk Survey. Although SCUBA-2 is late, the importance of the surveys remains high, and the capabilities of the instrument are still unique[2].

The most substantial increase in the capabilities available for Canada at submm wavelengths is the involvement in the Atacama Large Millimetre/submillimetre Array (also described in a separate paper [10]). Beyond the useful life of SCUBA-2, access to wide-field surveys could come from participation in a new project like CCAT [11].

In space (see [12, 13]) Canadians are involved in

[2] It is worth remembering that neither SCUBA-2 nor BLAST were mentioned in the 2000 LRP – the importance of the ability to respond quickly to special opportunities may not be unique to the submm band, but it has certainly been critical in recent years.

both Guaranteed and Open Time projects on *Herschel*, e.g. HerMES and Hi-GAL, and Canadians are also working on Galactic and extragalactic 'foreground' science projects using *Planck* data. In addition Canada is playing a role in plans for the SAFARI instrument on SPICA, which is expected to launch in the middle of this decade.

3. GALACTIC SCIENCE GOALS

3.1. *Star Formation*

Massive stars form from dense cores within molecular clouds, and are important for chemical enrichment, cycling the ISM into stars (see [14]). A full grasp of galaxy evolution requires understanding star formation in detail, but there are still many unsolved issues in the starformation problem. The youngest stars form in dusty cores – finding them demands wide submm surveys, with high resolution continuum and spectroscopic follow-up to probe accretion, outflows and disks.

There seems to be a similarity between the mass function of clumps and the mass function of stars – what precisely is that connection, and can we understand the origin of the Initial Mass Function (IMF)? This requires measurements that probe down to substellar masses and wide surveys to test the environmental dependence of the IMF. Detailed kinematic studies can only be done with heterodyne mapping, also typically covering large areas (e.g. Fig. 4).

Details of the formation, structure and evolution of stars and stellar systems are still poorly understood, largely because of the physical complexity, involving accretion, atomic and molecular cooling, astrochemistry, dynamics and magnetic fields. Theoretical modelling struggles to keep pace with the quality of the data, and observations must reach the scale of the protostars themselves – ultimately requiring space-based interferometers. To observationally determine how star formation results in a diversity of systems, including planets, we need a combination of spatial resolution, spectral resolution, wavelength coverage, mapping coverage and sensitivity.

3.2. *The Interstellar Medium*

For a complete picture of the Milky Way, one must trace the cycle of molecules from the diffuse ISM to planetary systems, again requiring wide-field mapping combined with targeted spectroscopy. Here digital spectroscopic advances seem likely to revolutionize the field, leading perhaps to the ultimate goal of connecting astrochemistry to astrobiology.

Astrochemistry is fundamentally about complexity – getting the big picture requires observations, analysis and modelling of many molecular and atomic lines and their correlations. This is also tied with the formation, distribution, composition and evolution of dust grains. We would like to follow the full lifecycle of dust, from asymptotic giant branch stars, supernovae and young stellar objects into the ISM and through to the 'death' of dust in star-forming regions. The resolution of HIFI on *Herschel* allows for detailed compositional and kinematic studies. SPICA will have similar resolution, but much improved sensitivity.

3.3. *Polarization*

The role of magnetic fields in the diffuse ISM is key for tracking the assembly of clouds and star-forming cores
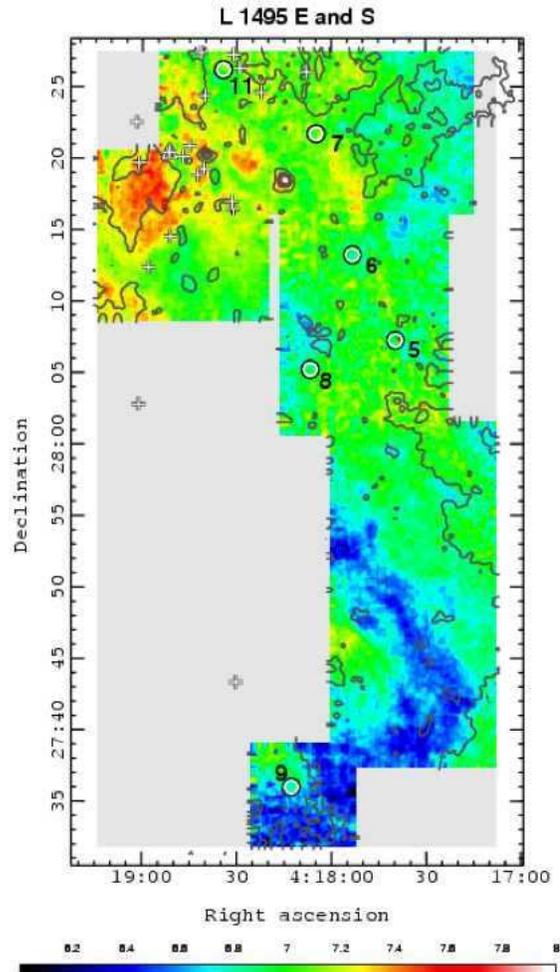

FIG. 4.— Recent example of a dynamical study of a low mass star-forming region: radial velocity map in Taurus, using CO 3−2 data-cubes from the HARP instrument on JCMT [15]. The colour bar shows velocities in the range 6 to $8 \, \text{km} \, \text{s}^{-1}$, while the contours show integrated CO intensity. Circles are $H^{13}CO^+$ cores, crosses are Young Stellar Objects and triangles are Herbig-Haro objects.

(Fig. 5) and feedback into the ISM (Fig. 6). Sub-mm polarimeters are complementary to other measurement techniques (such as optical polarimetry and HI Zeeman splitting) – dust grains become aligned and emit so that the polarization psuedo-vectors are perpendicular to the magnetic field direction. As well as the importance of magnetic pressure for star formation being unclear, details of grain alignment also need more careful comparisons between observations and modelling.

Studies of magnetic fields in the ISM regions are complicated by the fact that few observational means exist to characterize their strength and morphology. However, some of these techniques are well-suited to the submm window. For years the main tool for finding the orientation of magnetic fields in the plane of the sky has been to use using the dispersion of polarization measurements (the Chandrasekhar-Fermi method), which is only reliable using data with high enough spatial resolution. (another area where Canadians are leading [16]). Polarization of molecular lines such as CO can also yield important information when dust emission is weaker. And
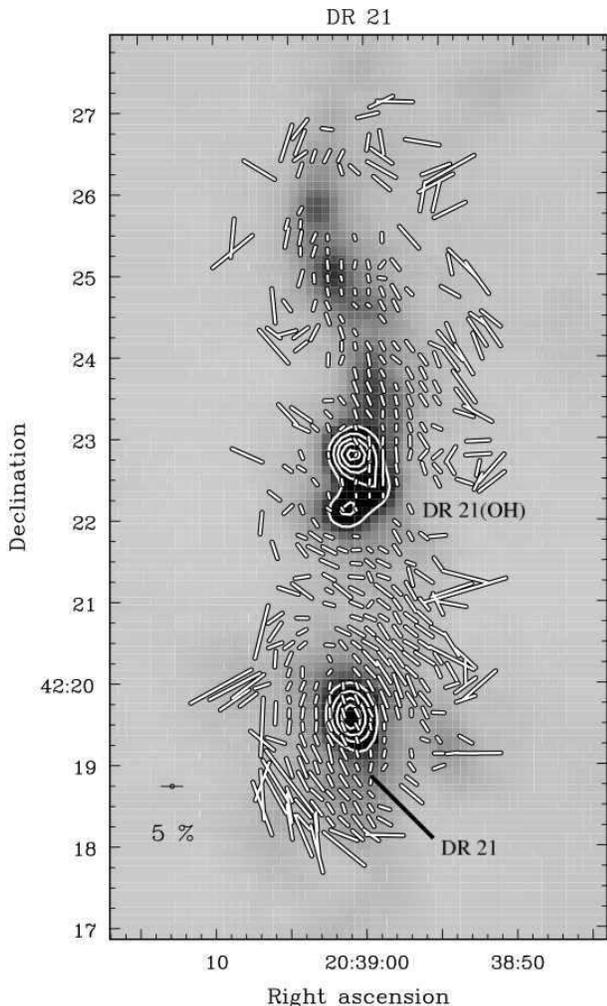
FIG. 5.— SCUBA $850\,\mu$m image of the high-mass star-forming filament DR21 (grey-scale, with contours starting at 5 Jy beam^{-1}). Polarization pseudo-vectors are overlaid (for pixels with sufficient signal-to-noise), showing coherent magnetic field patterns [17].

another technique compares coexistent neutral and ion molecular species to probe magnetic fields in turbulent clouds.

These techniques will help answer several outstanding questions – How are magnetic fields in spiral arms connected with those in molecular clouds? Does magnetism dominate the turbulent energy budget? What processes align the dust grains? Is there a difference between large and small grains? What is the anomalous emission seen as a foreground in CMB experiments?

SCUBA-2 POL is a Canadian led enhancement for SCUBA-2, and the BLAST experiment has been redesigned as 'BLAST-Pol', with polarization sensitivity. These facilities will help understand the relationship between magnetic fields in the ISM and in dense cores.

3.4. The Galactic Centre

The Central Molecular Zone is a region of about 200 pc radius around the centre of the Milky Way Galaxy, containing about $4\times10^7\mathrm{M}_\odot$ of warm molecular gas and dust. This is about 10% of the total ISM in the Galaxy, and can be used as a local template for studying gas-rich AGN. What is the dominant heating process (T is higher than
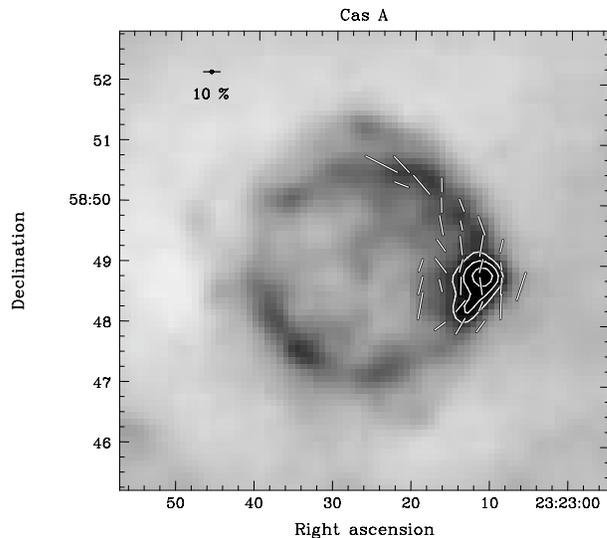

FIG. 6.— SCUBA $850\,\mu$m imaging and polarimetry of the Cas A supernova remnant [17], showing an ordered pattern in the shell.
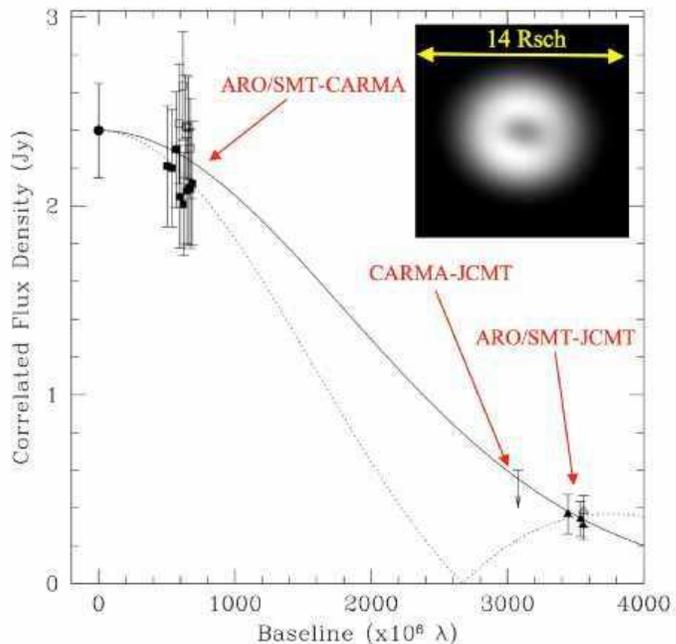

FIG. 7.— Measured values for the correlated flux density of Sgr A* as a function of baseline compared with 2 models. The solid line is for a simple Gaussian of FWHM of $0.037''$ (corresponding to $3.7\,R_{\mathrm{Sch}}$), while the dashed line is for the image shown in the inset, which has a silhouette in its accretion disk, caused by relativistic effects [19].

in the Plane)? What are consequences of the strong magnetic field? What is going on right down at the scale of the Schwarzschild Radius?

In the submm we can probe right into the obscured core of the Galaxy. Variability and polarimetry studies have already shown promise as tools for probing the complex dynamics in the Galactic Centre. Recent VLBI observations show that it is possible to see down to the event horizon [18], a prospect which will be improved
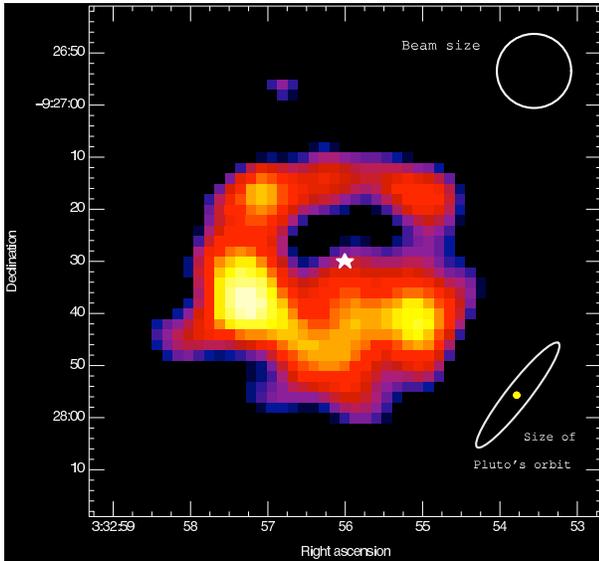
FIG. 8.— SCUBA 850 μm image of dust around the star ε Eridani (marked in the centre). The extended flux resembles a ring of circumstellar dust, perhaps corresponding to the Solar System's Kuiper Belt and also having intriguing asymmetries [20].
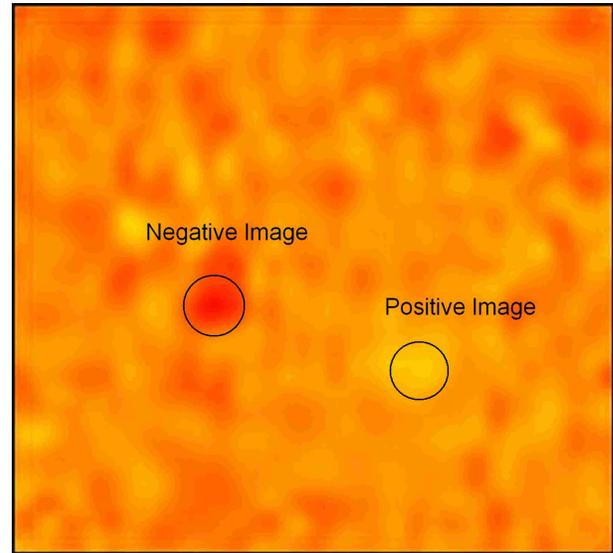

FIG. 9.— *Herschel*-SPIRE image of the dwarf planet MakeMake, using a differencing technique on observations taken tens of hours apart. This shows the potential for observing faint Solar System objects, even below the background confusion limit at these wavelengths (image from ESA and the 'TNOs are cool' *Herschel* Key Project).

with the use of ALMA.

3.5. *Planetary Systems and Disks*

The submm also allows us to probe cold disk systems around stars. Collisions around some stars have generated debris disks which can be relatively bright at these wavelengths, enabling us to study analogues of the Solar System's Kuiper Belt. Similar studies can be made of genuinely protoplanetary disks, as well as systems in transition. SCUBA allowed us to probe the structure of a few nearby disks (Fig. 8), while surveys with SCUBA-2 and *Herschel* will find new targets for detailed follow-up. Again this is an area where Canadians are leading the effort (see the separate White Paper [19]).

ALMA gives us the spatial resolution to probe disk structure in some detail, including radial variation of the spectral energy distribution. However, exploring the chemistry will be more challenging. An ambitious goal is to resolve water vapour in planet-forming disks – this will require the spatial resolution of a far-IR interferometer.

3.6. *The Solar System*

Submm observations have been used to investigate a diverse range of topics in our Solar System, including: the kinematic and temperature structure in terrestrial planetary atmospheres; chemistry in Jovian planets; albedos of asteroids; and dust and molecular physics in comets. These studies are only possible at submm wavelengths. Future work will involve using the new facilities, e.g. ALMA's more meaningful angular resolution, or increased sensitivity enabling Kuiper Belt objects to be studied (Fig. 9).

4. EXTRAGALACTIC SCIENCE GOALS

For starbursting galaxies the dust continuum contains the bulk of the luminosity, and photometry can straightforwardly determine dust temperature and emissivity.

Lines provide around 1% of the luminosity, and can be used to determine physical conditions, as well as to obtain redshifts. It is important to probe both the gas and the dust, in order to relate the fuel for future star formation to the emission from current stars.

The Far-IR/submm bands include 10 fine-structure lines from abundant species – CI, CII, NII, NIII, OI and OIII, plus mid-J rotational transitions of CO (Fig. 10). Extragalactic astrochemistry is in its infancy, but it is important to extend Milky Way studies to understand physical processes in nearby galaxies, and apply this knowledge to more distant Ultra-Luminous Infrared Galaxies (ULIRGs) and Sub-Millimetre Galaxies (SMGs). Single dish telescopes with wide-band spectrometers (perhaps CCAT in future) are useful for studying whole galaxies, while ALMA can resolve molecular cloud scales. Space-based instruments, such as SOFIA, *Herschel* and SPICA extend the wavelength (and redshift) range.

4.1. *Nearby Galaxies*

The ability to resolve structures within nearby galaxies enables detailed studies to be carried out over a wider range of star-forming environments than are accessible in the Milky Way. Super-star clusters in galaxy mergers, for example, can help to understand high-z galaxy formation. Specific molecular transitions probe quiescent gas, grain chemistry in photo-warmed gas, shocks, dense gas clumps and higher temperature gas. Questions that can be addressed include: How are star formation estimates from submm emission related to estimates from other wavebands (see [21])? What is the relationship between the global chemical structure of galaxies and their dynamical history? How do starbursts feed back on molecular clouds? How good is HCN as a star formation tracer? Can chemistry distinguish AGN from starburst luminosity? How does dust grain size and composition
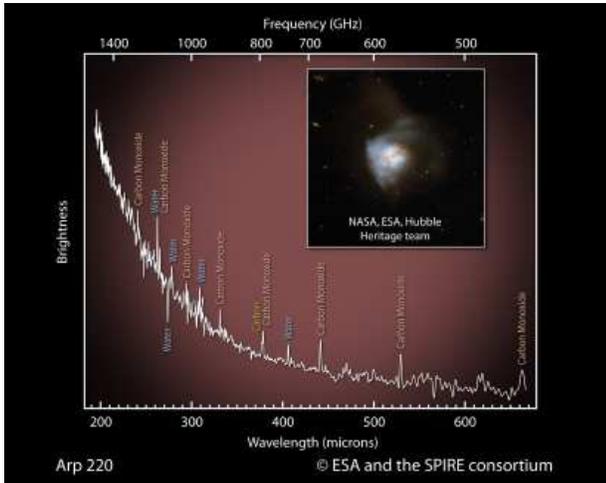
FIG. 10.— An early result from the *Herschel*-SPIRE Fourier Transform Spectrometer. This is a sub-mm spectrum of the relatively nearby starbursting galaxy Arp220, showing many individual lines – part of the 'Nearby Galaxies' Key Programme, in which Canadians are playing a leading role.

vary with environment and time?

4.2. *The Peak of Star Formation*

Submm observations can be used to determine global star formation history, and distinguish among models of galaxy formation. Star formation per unit comoving volume peaks when the Universe was perhaps 30% of its present age ($z = 1$–2). Galaxies with the highest star formation are also the dustiest, so often impossible to directly view in the optical. Long past their era of activity, SMGs or ULIRGs peak around $z \simeq 2.5$ (Fig. 11), and although rare they are extremely luminous, so they are a significant contributor to the global star-formation rate at high z.

ULIRGs are clearly related to mergers, as are AGN, but the exact relationship is currently unknown – how much of the rest-frame far-IR emission has a gravitational rather than nuclear origin? And do ULIRGs turn into quasars?

Theoretical understanding of dark matter is under control, but the baryonic mass assembly history of galaxies is much more complicated. Current submm telescopes allow us to probe the most extreme star-formers, and future facilities like ALMA (Fig. 12) will enable us to observe normal Milky Way-like galaxies at high z, not just the monsters.

Herschel has limited ability to carry out extragalactic spectroscopy – even the brightest far-IR lines redshifted into the submm are extremely faint for all but the most luminous galaxies at $z > 1$. So progress out to the highest redshifts will require the additional sensitivity provided through the use of a cooled telescope – SPICA, the 3.5–m cryogenically cooled Japanese-led telescope, is planned for launch in 2017.

4.3. *The First Galaxies*

The negative K-correction in the submm (Fig. 13) ensures that as soon as star-forming galaxies contain dust, they will be relatively easy to detect, even at $z \sim 10$. Ad-
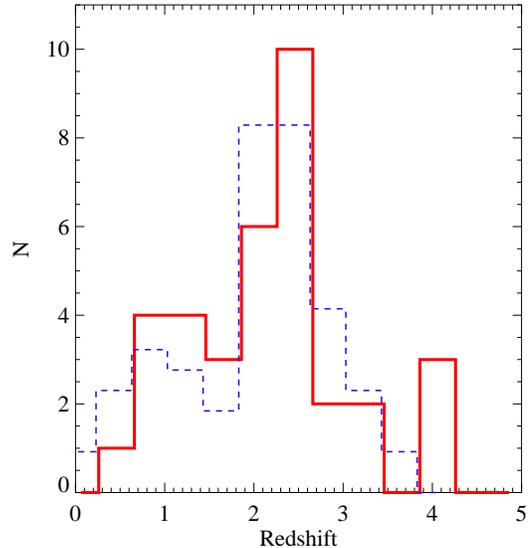

FIG. 11.— Redshift distribution of Submillimetre Galaxies (SMGs) [22]. The solid histogram is from the nearly complete GOODS-North sample, while the dashed curve is the larger sample of radio selected SMGs [23]. The average redshift appears to be $z \simeq 2.5$, with little evidence for a significant tail beyond $z = 4$.
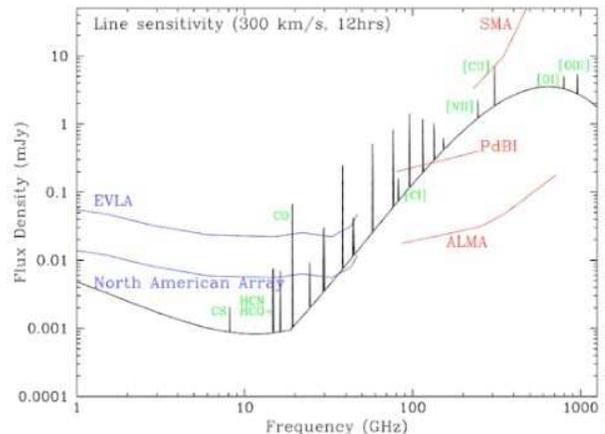

FIG. 12.— Model spectrum of the starburst galaxy Arp220, shifted to $z = 5$ and with several molecular and atomic lines labelled [26]. The red lines show the 1σ sensitivities for a 12 hour observation of a $300\,\mathrm{km\,s^{-1}}$ linewidth for the 3 submm interferometers: Submillimeter Array; IRAM Plateau de Bure; and Atacama Large Millimeter/submillimeter Array.

ditionally, redshifted far-IR lines such as from CII provide sharper diagnostics. Can we use these observations to help determine when the first stars and accretion-powered black holes formed? And at what epoch was the star formation *not* dust-enshrouded? Can we trace the end of the Dark Ages through cooling lines as the Universe transitions from a dustless to dusty medium? The sensitivity afforded by ALMA and eventually SPICA will help perform spectroscopic studies of the earliest objects.

4.4. *The Extragalactic Background*

The Cosmic Infrared Background is (probably) entirely composed of individual galaxies. A major current en-
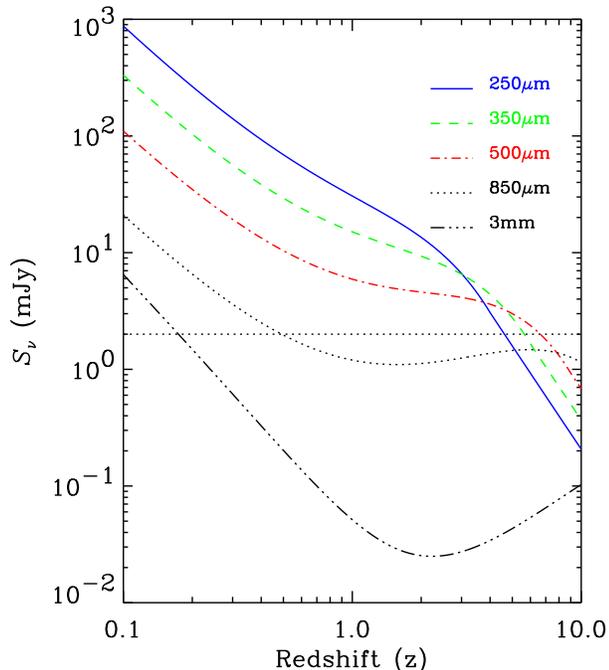
Fig. 13.— Galaxies of a given luminosity are almost equally detectable over a very wide redshift range at submm wavelengths. This is because of the so-called 'negative K-correction' pushing the observed band *up* the Rayleigh-Jeans part of the spectral energy distribution as the galaxy redshifts, compensating for the redshift dimming. This figure shows the spectrum of Arp220 redshifted in several different wavebands [24]. The horizontal line is at $2\,\mathrm{mJy}$, approximately the limiting $850\,\mu\mathrm{m}$ flux density for SCUBA.

deavour is to resolve the background and determine the luminosity function and evolution of the galaxies which comprise it. This becomes more difficult at longer wavelengths, where there is a greater contribution from high redshift sources, and where source confusion is increasingly severe (Fig. 14).

Precise measurements of the background and comparisons with sources can determine if there are missing components. Correlations in the background yield additional information about galaxy evolution within clustered dark matter haloes. This will be a major topic for wide surveys, with *Herschel*-SPIRE and SCUBA-2, for example. One unique aspect of SCUBA-2 is that the resolution available at $450\,\mu\mathrm{m}$ allows for most of the background to be resolved directly into sources down to 'normal' L_* galaxies (see Fig. 15).

4.5. *AGN and black holes*

As well as probing the first galaxies, we would also like to understand when the first super-massive black holes formed and determine the conditions which drive their evolution (see [27]). The submm band provides a means of studying the gaseous fuel through atomic fine structure lines and molecular transitions. High resolution spectroscopic imaging can probe galaxy dynamics and star-formation processes on sub-kpc scales, seeing through the dust which hampers most other wavebands.

The connection between star formation and AGN activity is still a great mystery (Fig. 16). Mergers provide a natural link, but details depend on physical processes which are hard to model. Moreover, the feedback of
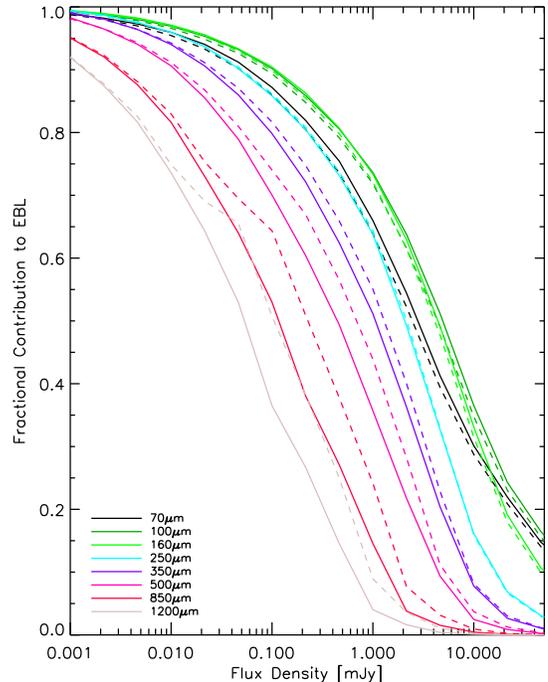

Fig. 14.— Model estimates for the fractional contribution to the extragalactic background from sources above a given flux density at different wavelengths (from [25]). The solid and dashed curves represent two different luminosity functions which are consistent with most of the current observational constraints. This shows the need for surveys using large dishes (small beamsizes), such as with JCMT or CCAT, since the fraction resolved at the confusion limit of SPIRE ($> 10\,\mathrm{mJy}$) is small. ALMA has the resolution to detect almost everything which contributes, but with small samples because of the small field of view.
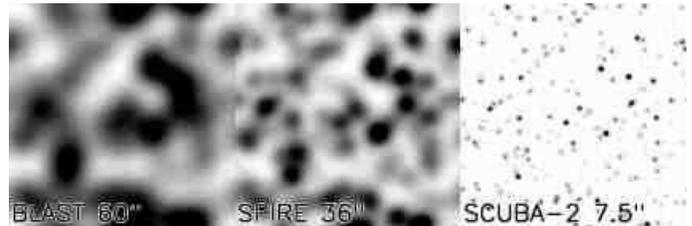

Fig. 15.— Comparison of the effects of the beamsizes of BLAST, SPIRE and SCUBA-2 at $450\,\mu\mathrm{m}$ in a deep extragalactic simulation. While great progress can be made through statistical studies of confused maps, SCUBA-2 will detect objects individually.

the AGN onto star formation is also poorly understood. Spectroscopically with *Herschel*, ALMA and SPICA are again just what is needed.

4.6. *Galaxy Clusters*

How much total power is emitted by galaxies in different environments? What types of galaxies dominate global star formation, and how do stars form within them? When and how did galaxies form and their metals accumulate? Do high redshift star-forming galaxies avoid overdensities like we see locally or is there a reversal in this relation (see also [29])? These and other questions involving the relationship between galaxies and clusters are only now becoming possible because of the sensitivity
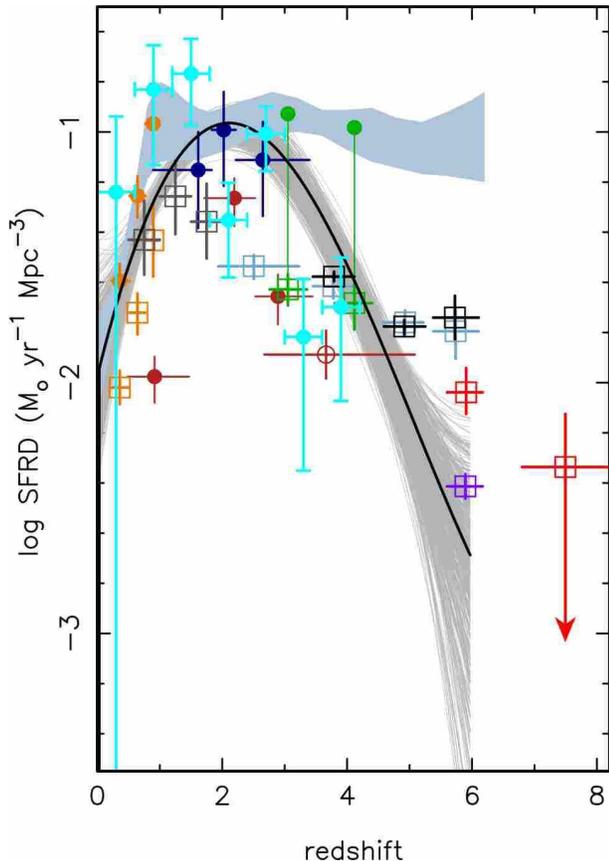
FIG. 16.— Star-formation rate density determined from a sample of SMGs (cyan points) compared with estimates from other methods (see [30]). The solid line and shading represent the space density of radio QSOs (arbitrarily normalized), showing the similarity between the history of star formation and black hole accretion.

to probe dark matter potential wells, including substructure, as well as constraining dark matter physics and the influence of super-massive black holes.

5. RECOMMENDATIONS

A wide range of science questions can be tackled using unique diagnostics at submm wavelengths. Most of them require deep and wide surveys encompassing tens to thousands of square degrees and tens of thousands to millions of galaxies. Detailed follow-up of targets demands high spatial resolution and sensitive spectroscopy. As a consequence of these drivers it is natural that a combination of facilities is required.

In addition to instrumental facilities, there are also other factors which will enable progress. Map-making at submm wavelengths (using iterative techniques to approach the maximum likelihood solution) has become computationally intensive, as has source extraction (using multi-wavelength Bayesian techniques for example), statistical analysis of images (e.g. with so-called $P(D)$ analysis) and comparison with models (including hydrodynamic galaxy mergers or turbulent ISM simulations). As specific examples, both BLAST and SCUBA-2 use cluster computing and have developed archiving plans through the Canadian Astronomy Data Centre (see [31] and [32]). A second factor is human resources – Canadians are behind most of their international partners in the ability to fund the postdoctoral researchers who can carry the complex analysis to fruition.

Among Canadian astronomers with submm interests there is a high degree of consensus in the following specific recommendations:

1. Complete JCMT Surveys

2. Vigorous involvement in *Herschel*

3. Prepare for ALMA

4. Develop plans for involvement in future survey instrument(s)

5. Plan for future space-based mission(s)

6. Support theoretical work

A decade ago we were struggling to make maps which encompassed more than a few star-forming cores or distant SMGs. With the coming of BLAST (Fig. 3), *Herschel* (see Fig. 17) and SCUBA-2 we have moved well beyond the 'one object at a time' science, and can now survey thousands of sources at once. Continuing this survey work and performing targeted follow-up with ALMA and other facilities means that we have a very productive decade ahead of us.

This White Paper is based on results from a huge number of papers and discussions with many of our colleagues. Due to the review nature of this contribution we have had to omit most original citations, but most can be found by tracing through the other reviews to which we refer.

of modern submm facilities.

The $850\,\mu$m atmospheric window is close to the peak of the Sunyaev-Zel'dovich (SZ) *increment*. Combination with more traditional measurements of the decrement improve the separation of the SZ effect from radio and star-forming galaxies within the clusters, as well as lensed background sources, potentially yielding estimates of the kinetic SZ effect to study cluster bulk velocities. Calibrating properties of galaxy clusters for use as cosmological tools requires comprehensive study, and here the submm observations will certainly help. In addition the high resolution provided by ALMA will enable detailed investigation of intracluster physics through the thermal SZ effect from substructure.

It is well-known that rich galaxy clusters can act as lenses for background SMGs. The steep number counts mean that we can use 'natures telescopes' to probe down to intrinsically much fainter objects at high-z. Hence wide surveys may uncover strong lensing candidates more efficiently than radio and optical surveys (see [30]). Once found, follow-up observations of such lenses can be used

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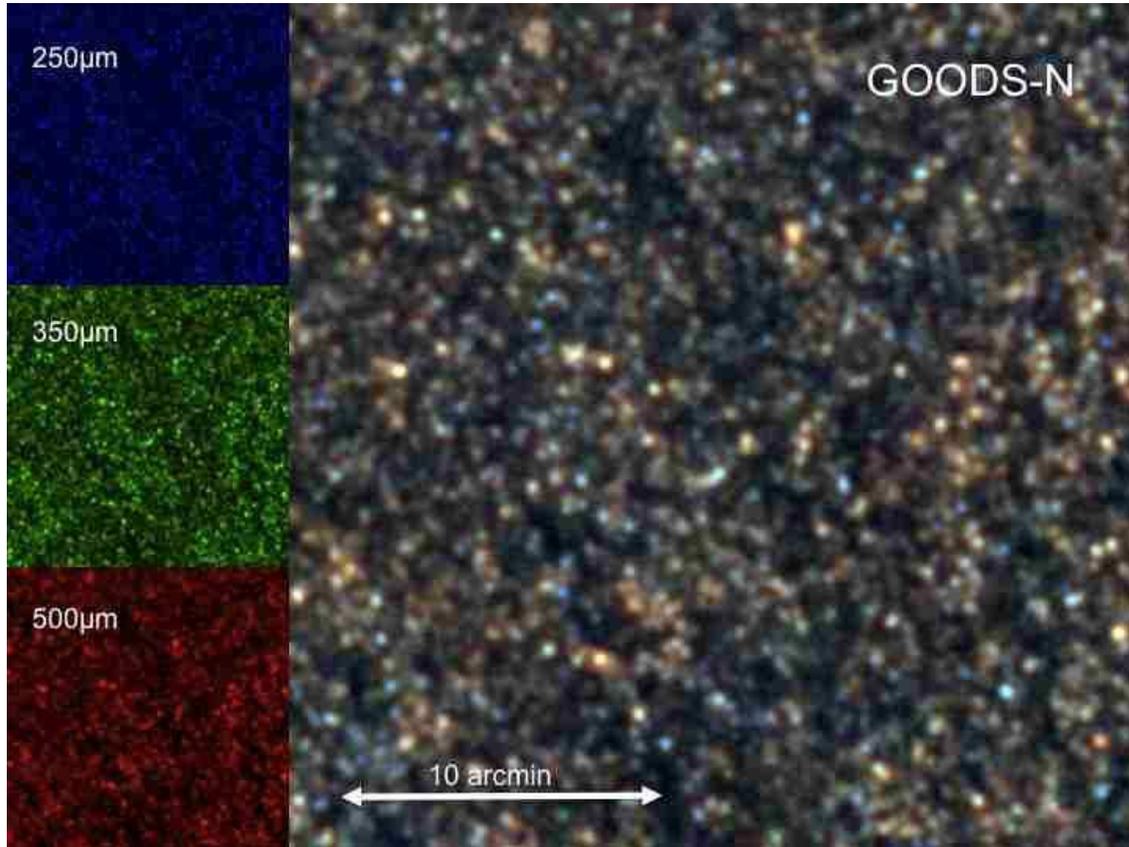
FIG. 17.— Composite colour image of the Great Observatories Origins Deep Survey – North field. This was imaged using *Herschel*-SPIRE as part of the HerMES guaranteed time project. Cite HerMES web-site [33], this particular figure put together by Gaelen Marsden for the HerMES press release. It shows the quality of SPIRE data, and the coming of age of extragalactic submm astronomy – this single image contains thousands of sources.

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