Extending the life of JCMT to 2020 and beyond

Executive Summary

A panel was set up by the Director, JCMT, and tasked with answering four questions, as follows:

1) Is there a world-leading science case for the JCMT up to 2020 and beyond ?
2) What new instrumentation is needed to accomplish this ?
3) What telescope modifications are necessary to accomplish this ?
4) How much will all this cost to within ~30% ?

The panel have undertaken both a technical and scientific study of various options and have consulted with the user community through an on-line discussion board and email list.

The panel believes that there is a strong science case for extending JCMT operations to 2020 and beyond, both in galactic and extragalactic science areas. Particular highlights for possible galactic science are wide area continuum and line surveys of and for extragalactic science the highest priority would be to conduct large-scale low-resolution spectroscopic surveys to complement the deep imaging surveys that will be carried out by SCUBA-2 and that could also be undertaken by a larger-format camera that the panel strongly recommends.

The highest priority modification to the telescope to enable the highest-impact science to be done would be to replace the current top-end with a larger (fixed) secondary which would allow a much larger field-of-view at the Cassegrain focus. An increase from the current 8 arcminutes to over half a degree is easily achievable at a relatively low cost of around £300k.

Another modification that was investigated in some depth is to replace the current surface with a new one based on technology developed for the ALMA dishes. This would allow routine diffraction-limited operations at 350 microns, with a consequent gain in angular resolution of 30% to 5.5 arcseconds and also an increase in sensitivity of around 40% at 450 and 80 % at 350 microns. This could be achieved at a cost of £5M. An alternative option is to upgrade the existing panels, an option studies in some detail in the mid-1990s, at a cost of around £2M. The panel considered these options worthwhile if funds were available, but at a lower priority than increasing the field-of-view with the existing surface and investing in new instrumentation.

In the medium term, the highest priority instrument would be a new camera to exploit the proposed larger field-of-view, requiring around 100,000 pixels. The panel believes this will be achievable by 2016 utilising the new KIDS technology. There was also strong support within the community, backed by the panel, for investment in a larger heterodyne, high-resolution (10^6), spectroscopic camera with greater than 100 pixels. The panel believes this should be achievable by 2020. In the longer-term the greatest impact of an enhanced JCMT would be to have a large-format multi-object (low-resolution ~10^3) spectroscopic camera.

Detailed costing of the proposed instruments are difficult, and notoriously unreliable, however the panel suggests that under the previous JCMT instrument-procurement model the approximate costs would be around £5M for the large-format, multi-frequency camera; and £8-10M for each of both the heterodyne array high-resolution camera and the multi-object low-resolution spectroscopic camera depending on whether JCMT was paying for any R&D or purely for instrument build. However the panel also proposes changing the JCMT procurement model to an open “build-to-a spec” announcement of opportunity one, where the telescope pays only for deliverable hardware, no staff costs and recompenses successful bidders with large blocks of guaranteed telescope time, spread over several years, after acceptance of the instrument.

1: Background

At the invitation of the Director JCMT, a small panel chaired by Prof. Walter Gear of Cardiff University has been looking into possible future science cases for extending the lifetime of the JCMT past the current JCMT Legacy Survey and indeed as far as 2020 and beyond. The terms of reference for the panel as well as its membership are appended to this report. The panel met via telecon on a number of occasions over the summer of 2011. Initial discussions converged reasonably rapidly and an outline summary of the panel's views was circulated to the JCMT community in July 2011 with an invitation to comment. Around 100 people signed up to an email list to discuss the report and about a dozen individual detailed responses were received. The comments were broadly in line with the discussion document circulated by the panel, although there was a stronger emphasis on high-resolution heterodyne spectroscopy than in the original report. The panel has reflected those views in this report by increasing the emphasis on that area of science.

It is important to put the capabilities proposed for JCMT in the 2020 era into context with other facilities. The IRAM 30m and the LMT 50m dish which should become operational in the next 2-3 years are both on sites that preclude observations shortward of 1mm except under exceptional conditions, so a JCMT focused on these submm wavelengths is not threatened by these facilities. The APEX 12m in Chile is on a comparable or possibly better site but is still smaller than JCMT, as are the 10m ASTE and CSO. Much has been made of the proposed CCAT 25-30m telescope superseding JCMT, and on a higher site in Chile. However it is important to point out that CCAT is not funded at this point, and that even if it does achieve funding, even in an optimistic scenario will not be commissioned until something like 2018 at the very earliest. With the upgrades proposed here and world-class instrumentation JCMT will remain competitive in the 2020 era, in the view of the panel.

The proposals presented here are driven by the science that JCMT might do in the 2020 era; however in writing this report the panel found it easier to put this in context with possible technical developments, a view echoed by the comments from the community when reading the note circulated to them, so below we present the possible telescope upgrades and instrument concepts first, followed by the science that could be done.

2: Upgrades to the Telescope

2.1: Larger Field-of-View

Many of the science drivers outlined below lead to the conclusion that a larger focal plane would strengthen the case for extending the lifetime of JCMT. The panel therefore explored the possibility of altering the optics of the telescope to achieve this. Appended to this main report is a detailed report on optical design by David Henry. The main conclusion is that it should be relatively simple and inexpensive to replace the top-end of the telescope with a larger, fixed mirror and achieve a FOV of around 30 arcminutes, i.e. half a degree, compared to the current 8 arcminutes. In fact the optical design (Option 4a in the appended report), with a 1.5m secondary mirror (twice the size of the existing secondary), a slight alteration to the shape of the primary surface from a parabola to a hyperbola (well within the range of the existing adjusters), and clearing some mechanical structures around the central hole in the primary (resulting in clear aperture of 750mm rather than the current 676 mm), result in a **diffraction-limited field of view of 37.2 arcminutes**.

Although the secondary mirror is twice the diameter of the existing one in this model, because modern bolometric cameras do not require a chopping secondary, this can be fixed, doing away with much of the complexity of the existing top-end, although a three- axis focus drive would still be desirable. One possible disadvantage of the proposed scheme is that the focal plane is very close to the rear of the primary surface, and also that it would no longer be possible to relay this large a FOV out through the elevation bearings to where SCUAB2 is currently mounted. One option could be to turn JCMT into a single-instrument telescope with, for example, a camera filling this large field, rather like WFCAM on UKIRT. The panel believes the science case for operating JCMT to 2020 is strong even if it meant single-instrument operation; however since there are strong science cases and community support for spectroscopic instruments as well as imaging alternative schemes for flipping the field to a second instrument were explored. A possible scheme that would allow 2 instruments is shown in Figure 1(b), however this would need further detailed work to ensure that it was physically achievable within the mechanical constraints of the telescope structure.

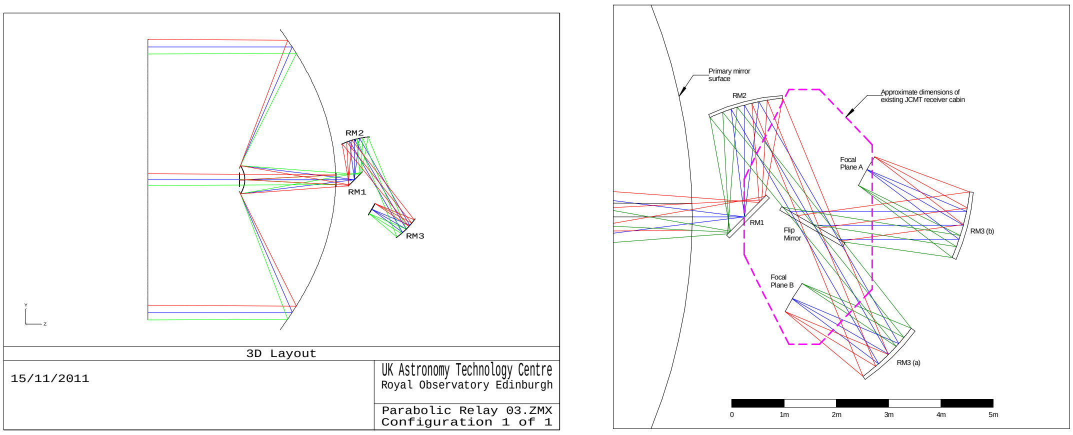


Figure One: *(left) optical layout for the 37’ FOV with a relay behind the primary (right) blow-up of the relay showing how positions for 2 instruments could be created.*

The approximate cost of replacing the secondary mirror would be £100k, and another £200k for the optics behind the primary. If the existing receiver cabin had to be removed and/or replaced the costs could rise significantly but should remain significantly less than ~£1M.

2.2: Upgrading the Surface

The panel also examined replacing the telescope surface, which would result in an improved rms and higher efficiency particularly at the highest frequencies. This possibility has been investigated in some detail in the mid-1990s and the panel was able to access a report to the JCMT board from that time. Although technology for new panels has moved on since then (see below) the report also investigates the option of reworking of the existing panels to reduce the scalloping (edge-curl) that they currently show, and this analysis is still valid. The conclusion was that with a cost of around £2M the rms could be improved from 25 to 18 microns resulting in an improvement in sensitivity of 27% at 450 and 47% at 350 microns.

Utilising the advances in materials since the 1990s and the developments for ALMA an alternative solution would be to completely replace the panels and backing structure with an ALMA-like design. A report was commissioned from EIE, engineering consultants who were very keen to offer their analysis based on their experience of working with ALMA. Their very detailed report is appended. With this technology **an rms of 13 microns could be achieved**, giving an improvement in sensitivity of 43% at 450 and 80% at 350 microns, and it might also be possible to remove the wind-blind. The cost of this option is around £5M.

The panel concluded, however, that the gains in resolution and sensitivity by focussing more on 350 microns rather than 450 microns were not as great as increasing the field of view of the telescope. They would prefer to see investment in new instrumentation to exploit the proposed larger FOV. This viewpoint was also endorsed in the community responses.

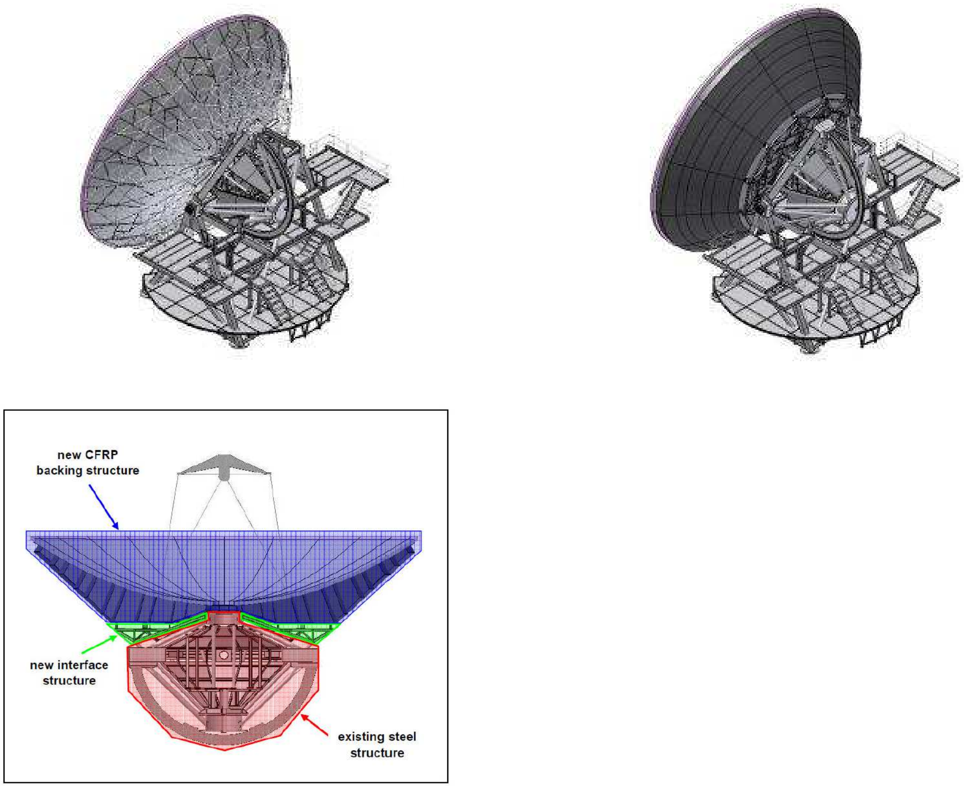


Figure Two: *(top left) current JCMT (top right) proposed EIE solution (bottom) section view of EIE proposal*

3: New Instrumentation Development

SCUBA-2 is now finally able to deliver the massive increase in mapping speed the community has been awaiting, and there are strong legacy programmes that will keep the JCMT busy for the remainder of its currently-defined operational lifetime. In the 2020 era however, particularly with the proposed FOV upgrade, the JCMT will require new instrumentation. These fall into 3 categories:

(i) New, very large-format cameras based on Kinetic-Inductance Detector (KID) technology. These devices are much simpler to manufacture and operate than the TES detectors used in SCUBA-2 and are already being deployed on other large mm/submm telescopes such as CSO and IRAM 30-m Telescope. The panel estimates that a 100,000 pixel KID camera to exploit an enlarged FOV at JCMT could be built by 2016.

(ii) Larger format, heterodyne, high spectral resolution instruments for galactic and low-redshift mapping of the interstellar medium in galaxies. The complexity of LO feeds, etc., have prevented technology in this area from moving forward at anything like the speed of the purely imaging cameras, but the panel believes that a 100 pixel (or more) 345 GHz instrument could be built by 2018.

(iii) Large-format, low-resolution, multi-object, spectroscopic imaging arrays for extragalactic science. The panel believes that developing a capacity for obtaining spectroscopic redshifts of hundreds of high-z galaxies per night is the strongest possible case for JCMT2020. The technology to allow this is still premature, but the panel believes that such an instrument could be built by 2020.

3.1: Large-format KIDs Array Camera

Kinetic Inductance Detectors are superconducting resonators which change their resonant frequency and quality factor (Q) when incident radiation is absorbed in the superconducting material. Each resonator is designed to have a distinct resonating frequency, typically in the GHz range, with high Q ($>10^6$) which means that 1000s can be read out on a single coaxial cable. They are very simple devices which can be fabricated in relatively basic clean-rooms as they do not require the multi-stage fabrication processes of TESs for example. The readout electronics is also very much simpler than the superconducting SQUIDs required for TESs. KID cameras have been demonstrated on several telescopes and the IRAM 30m have just commissioned an 8000 pixel KID camera (see Annex). If JCMT were to conduct a similar commissioning exercise during 2012 then there is no reason why a multi-frequency camera filling an enlarged FOV could not be built to replace SCUBA-2 by 2016.

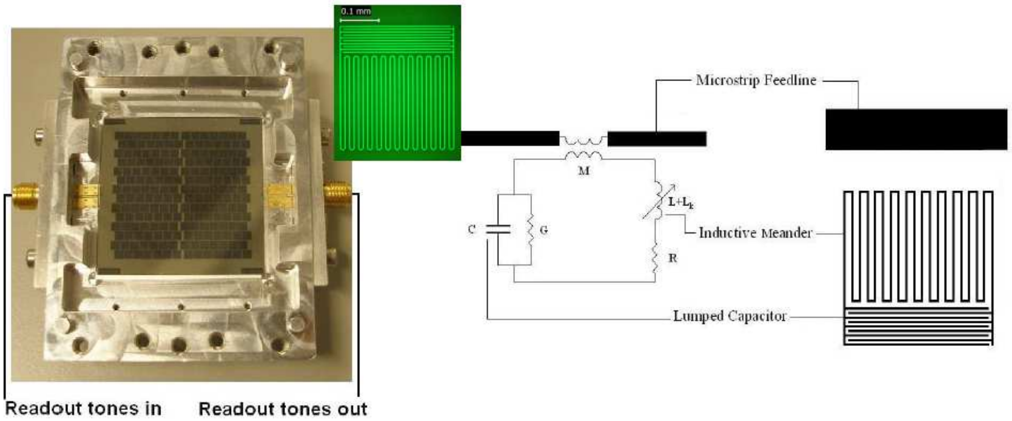


***Figure Three**: Left: Photograph of a 196 pixel (14x14) array of LEKIDs designed for 2 mm wavelength observations at the IRAM 30 m telescope. Inset: Photograph of Aluminium LEKID. Right: Schematic of a LEKID equivalent circuit.*

Based on costings recently done in response to the IRAM 30m AO we can reasonably accurately estimate the cost of a 10^5 pixel KID camera at £4-5M.

3.2: Heterodyne Array Cameras

The HARP 16-pixel heterodyne camera on JCMT is still one of the largest in the world, and heterodyne technology has not developed at anything like the pace of imaging arrays. This is due to the complexity of the technology of the LO injection, mixing and amplification, with each pixel needing to separately assembled, and the backend spectrometers. However there have been advances, at Arizona in particular developing units of 8 heterodyne pixels packaged together for stacking into an array of 64 pixels for the "Supercam" instrument on the HHT. A reasonable target therefore would be a 100 pixel heterodyne array camera by 2018.

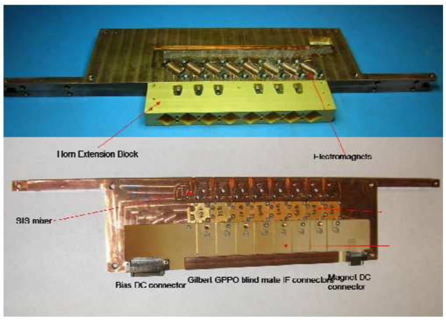
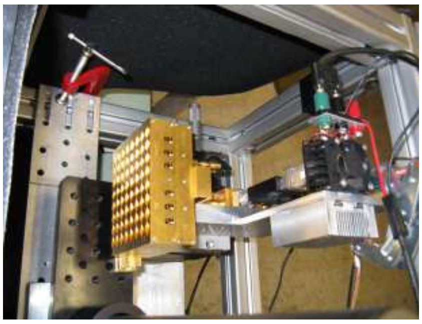


Figure Four: *(left) A 1x8 mixer module fully assembled (top) and top removed (bottom) (right) The Supercam 64 pixel Lo divider block*



The panel has not had access to information on costing for an instrument like the Supercam for HHT, however based on previous experience, and assuming that the JCMT did not have to fund a large R&D programme then it estimates the cost to be in the range £8-10M. The largest uncertainty is the cost of the very large backend capacity that would be required if full bandwidths are maintained for each pixel. There have been significant advances in digital electronics for signal processing in the past decade but the cost would still be likely to be about half the total estimated.

3.2: Large-Format, Low-resolution Multi-object Spectrometer Camera

The ultimate instrument for extragalactic applications is a large-format camera filling the FOV of the telescope in which every pixel is also a spectrometer. The simplest way to do this is to put a Fourier transform spectrometer (FTS) in front of an imaging camera. JCMT already has the FTS for SCUBA-2, although it has not yet been commissioned, but experience will be gained with this and JCMT should be in a world-leading position. However whilst the FTS is the simplest solution it does not offer the best sensitivity, since each detector still sees all the background in the band all the time. Greater sensitivity is achieved by splitting the band up into resolution elements with a separate detector for each, such as in a grating instrument, but at the expense of course of greatly increased complexity. Gratings are bulky and expensive and therefore not practical for very large format spectroscopic multi-object imaging. Concepts are currently in development in the UK, Netherlands and the US for such instruments at mm wavelengths. In all cases the basic idea is to have a microstrip behind each pixel with stubs acting as filterbanks with a KID detector on each stub.

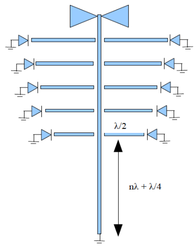
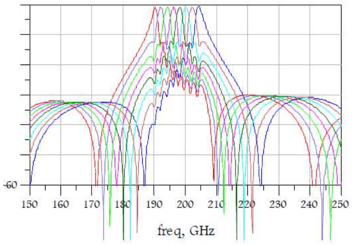


Figure Five: *(left) Basic concept for a "spectrometer on a chip" (right) simulated spectral response*



This type of device is still in the early development phase, however this technology should be proven with single-pixel or small multi-pixel instruments by around 2016 in which case it is not unreasonable to expect that a large-format instrument could be on the telescope by 2020. The cost is again very difficult to estimate, but assuming JCMT did not have to pay for all of the R&D then the panel estimates the instrument build cost to be around £8-10M

4: Outline Science Cases

(a) Extragalactic Science

(1) Continuum Imaging

1.1: Large-area confusion limited surveys

With a very large FOV telescope and a next-generation camera to exploit it, JCMT could lead the way in conducting very large area (>1000 square degrees), confusion limited surveys of the extragalactic sky, creating a definitive legacy data set. It is possible to imagine a JCMT survey which reaches the confusion limit across a large fraction of the available sky, the ultimate legacy programme.

Figure Six: *A 3-colour image of the 4x4 degree science demonstration field from the Herschel ATLAS survey. There are 7000 galaxies already identified in this image, which is only 1/40th of the final ATLAS survey. SCUBA-2 will conduct a survey of comparable area to this image with better angular resolution and hence lower confusion limit in around 1000 hours. With an instrument filling the proposed larger FOV the mapping speed to the same depth would be increased by a factor of ~100 so 1000 square degrees could be covered in the same time and a large fraction of the visible sky in a instrument it is possible to conceive of mapping most if not all the northern sky in a realistic timeframe.*

The science legacy if such a survey would be huge, and include many new discoveries, however we can already identify some likely outcomes: such a survey would be highly complementary to the all-sky Planck survey, identifying sources at higher angular resolution and sensitivity. These data will improve both the Planck secondary anisotropy studies and new cluster identification, as well as identify objects suitable for detailed ALMA follow-up. The combination with Planck data will remove some significant degeneracies in cosmological parameter estimation, including neutrino mass. The preliminary results from the Herschel ATLAS project has shown that such a survey should also find 10000s of lensed objects that can be used to test GR and improve number counts below the confusion limit. A large-area survey will also find many clusters, and high-z proto-clusters, allowing detailed investigation of the star-formation history as a function of cluster environment from z~2 to today. Many thousands of nearby galaxies will also be found in this survey, allowing detailed investigations at redshift zero in large statistical samples for comparison with the unresolved galaxies found at high-z. The high angular resolution of JCMT relative to Herschel will allow de-blending of confused sources, especially at the 450 microns band that overlaps with the Herschel 500 micron band (or even more so at 350 microns if the dish surface were upgraded). The longer wavelengths will also result in a greater sensitivity to high-redshift sources, which is where the greatest uncertainties in galaxy formation and evolution currently lie.

1.2: Detailed mapping of gas and dust in low-redshift galaxies

With increased resolution possible in relatively nearby galaxies, we can study in detail the star-formation process, its efficiency, and its dependence on factors such as environment, metallicity, gas fraction, bars, etc., and make comparisons with even more detailed investigations within our own Galaxy. The NGLS legacy programme will observe 155 galaxies in CO and dust emission. With larger-format instruments for dust imaging and spectroscopy, such observations will be made much faster, and hence much larger, less-biased samples can be studied. Complementarity with existing Herschel surveys is vital here as many examples of possible long-wavelength excess dust emission are being found, which complementary JCMT data will be essential to clarify.

To a large degree, the continuum observations could be achieved within the large area continuum survey described above (1.1) but targeted observations of individual galaxies outside the large survey area will also be necessary. Spectroscopic mapping of emission lines is also important, and a larger Heterodyne camera would be used for high resolution studies, but because of the large linewidths due to the range of velocities in most galaxies an FTS in front of a large-format camera, or a low-resolution spectroscopic imaging instrument would be sufficient in most cases.

As well as being critical to understanding the processes of star formation, studies of large low-redshift samples are also essential for interpreting the necessarily sketchy information obtained from high-redshift galaxies from deep cosmological surveys.

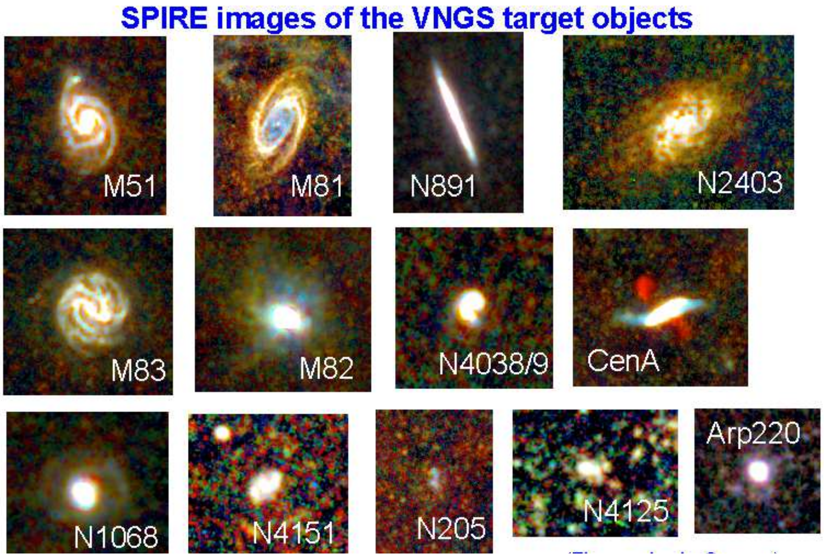


Figure Seven: *Herschel SPIRE 3-colour images of the galaxies in the GT nearby galaxies programme. Another 60 galaxies are being studies in similar depth by the KINGFISH survey. SCUB2 NGLS legacy programme plans to observe ~150 galaxies, but with a faster camera many more could be observed across a wider range of properties in large statistical samples, and a larger spectroscopic camera would enable much mode detailed and deeper line studies.*

1.3: Nearby clusters

High-resolution studies of nearby clusters provide an opportunity to investigate in detail the effect cluster environment has on galaxy properties, with a sample of objects all at similar distance. The Herschel Virgo Cluster Survey (HEViCS) has found clear evidence of extended emission features caused by galaxy interactions in that cluster. Clusters also contain large numbers of dwarf galaxies; other Herschel observations have indicated these galaxies have SEDs and possibly dust properties very different from those of spirals. Longer wavelength JCMT data will be critical for understanding these differences. Even with SCUBA-2, it will be very difficult to map the large areas required of nearby clusters (HEVicS covers 64 square degrees) but a larger format camera would allow study all major Northern Hemisphere clusters, i.e., Fornax, Ursa Major and Virgo.

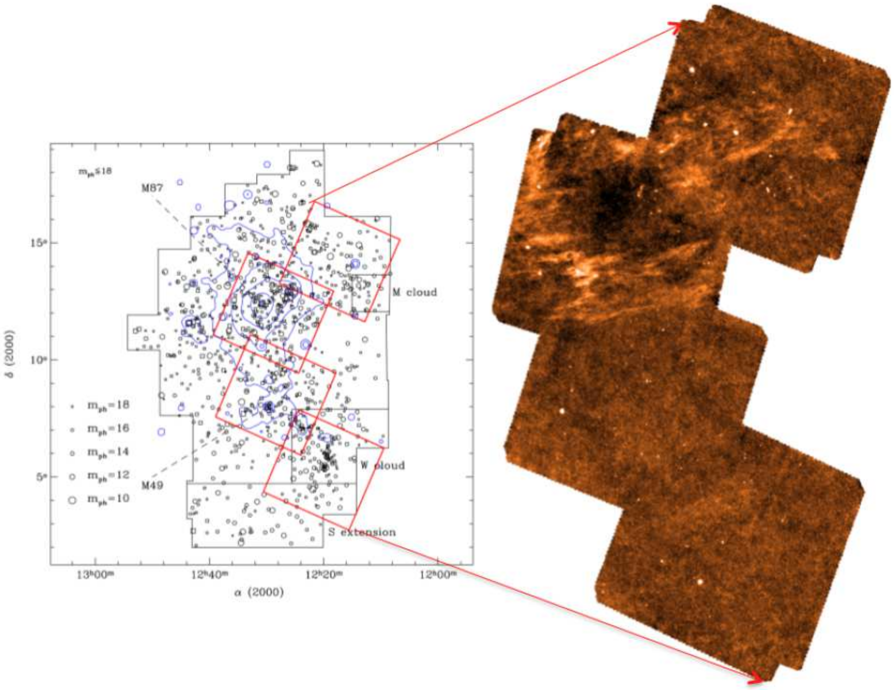


Figure Eight: *(left) Positions 2000 galaxies from the Virgo Cluster Catalog (VCC) with the 4 HEVICS fields marked (right) The Herschel Virgo Cluster Survey (HEVICS) 250micron image. It would be impractical to make a similar image with SCUBA-2, but with the proposed increased FOV and larger camera a complementary 850 image could be made in approx 600 hours.*

1.4: Sunyaev-Zeldovich/Clusters

The South-Pole Telescope (SPT) and Atacama Cosmology Telescope (ACT) have undertaken large area surveys at 150 GHz to search for massive galaxy clusters through their Sunyaev-Zeldovich signal. Both of these facilities are in the South, however, and no comparable survey has been so far undertaken in the Northern Hemisphere. With the improved resolution of JCMT over the 6-m ACT in the equatorial region of overlapping sky, it will be possible also to observe many clusters discovered by ACT at higher angular resolution and remove point sources, constrain gas temperatures and densities, and systematically measure kinematic effects both within clusters and for entire clusters.

1.5: CMB Science

Complementarity with the Planck all-sky data has already been mentioned but JCMT can also itself be a powerful instrument for CMB science at lower frequencies (150 GHz) than it has historically operated. Surveys of CMB fluctuations over 10s of square degrees at ~30” resolution can search for non-Gaussian fluctuations caused by, for example, cosmic strings or primordial magnetic fields. This has not historically been an area of activity for the JCMT community but with the proposed increased FOV this could be an area where a PI-led instrument for dedicated use in relatively poor weather might be appropriate.

(2) Low-resolution multi-object spectroscopy

2.1: Redshifts (using CII or CO) for objects found in large area surveys

Even the largest SCUBA and MAMBO surveys produced only 100s of high-z galaxies, of which the most interesting and brightest could be followed up spectroscopically with interferometers such as IRAM PdBI and SMA, as well as single-dish grating spectrometers such as Z-SPEC and ZEUS. There are, however, already ~10^5 sources in catalogs from the HERMES and H-ATLAS surveys, and a further order of magnitude increase is likely from the SCUBA-2 Legacy Surveys. Possibly even more can be expected from larger-area JCMT2020 legacy surveys, making this kind of source-by-source follow-up impractical. This is true even with ALMA, since ALMA will only be able to observe one such source every few minutes, and will have many calls on its observing time. It is also important to note that of the 7000 or so sources identified in the Herschel ATLAS preliminary survey area, only around 1/3rd had optical IDs, so although redshifts may be found from other wavelengths, because of the heavily obscured nature of most SMGs, observing lines in the submillimetre region is ultimately the best hope for an unambiguous identification. This is particularly true for the highest-redshift sources, for example the highest redshift (z=4.2) object for which a submm spectroscopic redshift has so far been found in the Herschel surveys had no unambiguous optical ID.

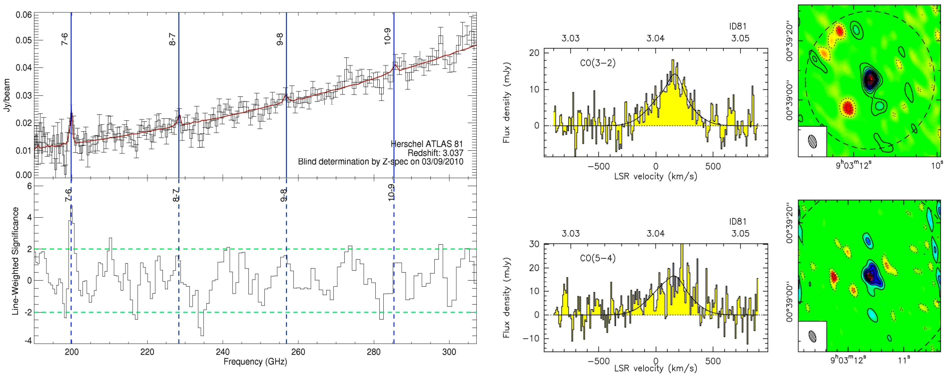


Figure Nine: *(left) Z-Spec grating spectrometer "blind" z= 3.04 determination of a lensed object in the HATLAS SDP field (right) confirmation of the redshift with IRAM interferometer.*

Therefore, the science case for technology development leading to large-format multi-object spectrometers is extremely strong. Developments have already started in the UK and USA on detector technologies that allow effectively a camera that can also obtain a spectrum on each pixel, albeit at low-resolution compared to heterodyne devices, but still adequate for redshift purposes. An instrument with ~1000 such pixels would allow efficient spectroscopic follow-up of all but the faintest sources found in the SCUBA-2 and Herschel surveys over a period of a few years.

2.2: Blind spectroscopic surveys

With an imaging survey there is no point in going much below the point where the field is confused, i.e. it is impossible to separate individual sources. If however one also has spectral information it becomes possible to separate objects along the line-of-sight and reduce the confusion considerably. With the multi-object spectrometer described above, it would be possible to conduct "blind" surveys where source redshifts can be obtained at the same time as their SEDs. Identification of redshifted CII 158 micron or high-J CO lines should be achievable in around 2-4 hours per pixel.

In such a large-area, "blind" spectroscopic survey, individual clusters overlapping in the sky could be separated. The Baryon Acoustic Oscillations (BAOs) imprinted in the early Universe and identified at optical wavelengths by SDSS could then be used as a standard ruler to look variations with redshift, and thus measure the equation of state of the dark energy.

(b) Galactic

(1) High-resolution Spectroscopy

1.1. Line Surveys of the Galactic Plane

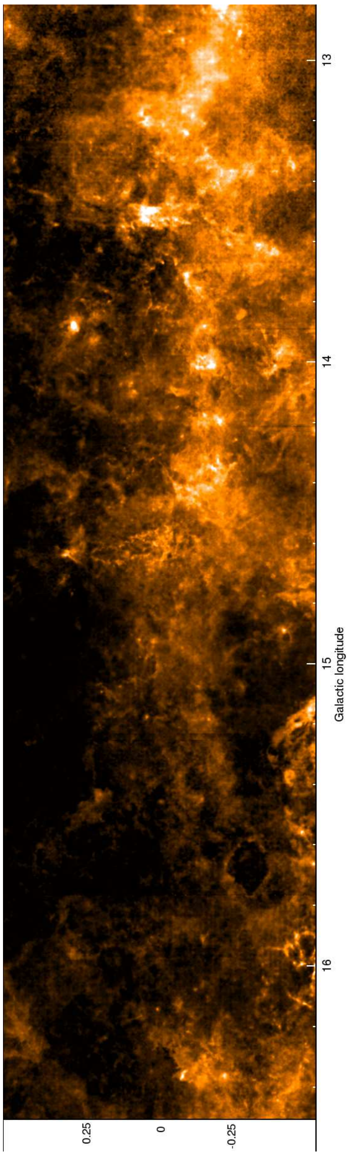
Although intense emphasis has been placed on continuum studies of the Galactic Plane in recent years there have been relatively few complementary studies of molecular line emission, beyond ones at relatively low angular resolution, e.g., the CO surveys by the CfA 1.2 m telescope of the entire Plane (at ~10' resolution) or the FCRAO 14-m telescope of the inner Galactic Ring (at ~1' resolution). Yet, surveying line emission at resolutions matched to the continuum surveys is crucial to provide complementary kinematic information about Galactic structures detected in the continuum. For example, line surveys of comparably high angular resolution provide an effective means to reduce line-of-sight confusion. In addition, line surveys provide velocity information about the motions of clouds in the Galactic Plane, yielding critical data about their distances, internal dynamics, and relative kinematics. Moreover, line surveys can constrain not insignificant amounts of line "contamination" that is included in the large bandpasses of continuum bolometers, yielding more accurate continuum fluxes without systematic overestimates of intrinsic dust brightness.

A new, large-format focal plane heterodyne array (or possibly even a new, large format low resolution multi-object spectroscopic imager) would make obtaining CO 3-2 maps of the Galactic Plane tractable, and provide the crucial information needed to complement the highly successful continuum Plane surveys. Indeed, some preliminary observations of a limited range of the Plane have begun with HARP, and a total of ~24 deg^2 have been observed so far at $l = 10$-$16°$, $|b| < 0.5$ and $l = 16$-$52°$, $|b| < 0.25°$ over ~80 hours (of relatively poor weather; see Figure 10). Though impressive, this swath comprises only 5% of the Galactic Plane that will be nominally observed by Hi-GAL. An array with a larger footprint than that of HARP (i.e., 2'), and a dedicated allocation of survey time, would allow a more rapid acquisition of these important Galactic data. In addition, it may be possible to implement a new design in the heterodyne case to allow simultaneous maps of the Plane in important lines other than CO 3-2. For example, perhaps ^{13}CO 3-2 and C^{18}O 3-2 could be observed, probing optical depths and cloud densities. In addition, $\mathrm{HCO^+/H^{13}CO^+}$ 4-3 and $\mathrm{HCN/H^{13}CN}$ 4-3 could be possibly observed as well, to probe for infall motions in denser gas within Galactic Plane GMCs. A new backend with narrow spectral windows definable over a wide frequency range could be useful in this regard.

1.2 Focused Surveys of $\mathrm{N_2H^+/H_2D^+}$ Emission in Nearby Star-Forming Clouds

In the coldest interiors of prestellar cores, many heavy-element-bearing molecular species like CO freeze-out onto dust grain surfaces. This means that such molecules cannot be used to trace the kinematics and dynamics of core interiors, yet these locations are precisely where mass accumulation occurs and protostellar collapse likely begins. Only a few molecules have been shown to be resistant to depletion onto grains, and are good alternative tracers of such environments. One species, $\mathrm{N_2H^+}$, remains abundant possibly because $\mathrm{N_2}$ takes a longer time to form than CO. Another species, $\mathrm{H_2D^+}$, becomes actually overabundant due to the loss of CO, as well as due to a reaction where at low temperatures its formation is favoured over its destruction ($T < 20$ K). Lines from both molecules have been shown to trace well the extents of cores seen in continuum emission, e.g., in previous HARP observations of $\mathrm{N_2H^+}$ 4-3 and $\mathrm{H_2D^+}$ 1_{10}-1_{11} at 372.4 and 372.2 GHz respectively (see Figure 11; a lucky coincidence of nature is that these two lines are very close in frequency, so they can be observed simultaneously quite easily).

A major problem with observing the N_2H^+ and H_2D^+ lines at 372 GHz is that extremely dry weather conditions (i.e., band 1; $\tau_{225} < 0.05$) are required to detect them. In addition, these lines can be relatively weak, e.g., H_2D^+ 1_{10}-1_{11} has been observed to have a typical peak brightness of ~1 K towards several prestellar cores. As a result, significant investments of scarce dry observing time are also required. Such limitations have meant that HARP could only be used to detect emission from these two lines from a relatively small handful of locations, though hundreds of prestellar cores have been detected in Herschel surveys of nearby molecular clouds. A new focal plane array, one larger and perhaps more densely packed with receivers than HARP, would utilize this scarce time much more efficiently, allowing large samples of core interiors to be probed for the first time.



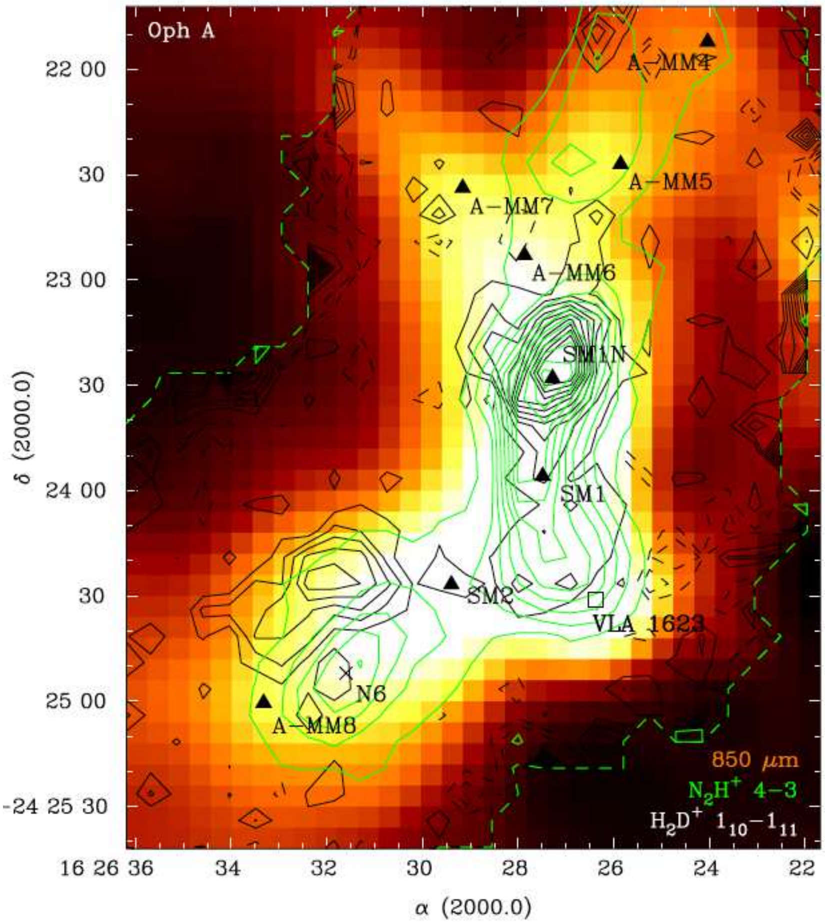


Figure Ten: *(left) A small sample of recent Galactic Plane observations made with HARP at l = 12.8-16.5°, |b| < 0.5°. The emission shown is the integrated intensity of the CO 3-2 line. .*

Figure Eleven: *(right) Integrated intensities of the* N_2H^+ *4-3 (green contours) and* H_2D^+ 1_{10}-1_{11} *(black contours) lines at 372.4 and 372.2 GHz respectively observed towards the Oph A filament with HARP overlaid onto the 850 μm continuum. The* N_2H^+ *data trace the continuum data quite well, and the* H_2D^+ *data show regions of enhanced abundance near prestellar cores in the filament. The line data required ~20 hours of integration time to complete in band 1 weather.*

(2) Continuum Imaging

2.1: Wide continuum survey of the Galactic Plane

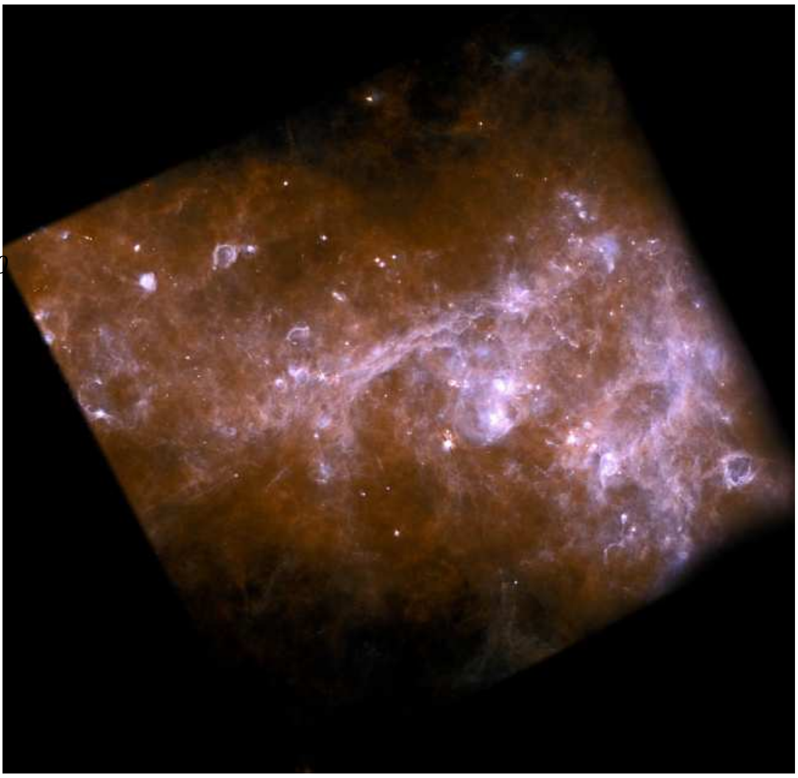


Figure Twelve: *A square-degree field of the Galactic Plane centered at* $l = 312^\circ$ *obtained by the Hi-GAL consortium with the Herschel Space Observatory (see http://herschel.cf.ac.uk/results/galactic-plane-centaurus). The image is a colour composite of emission at 70 μm (blue), 250 μm (green), and 500 μm (red). The image reveals some of the filamentary structures detected in the Plane by Hi-GAL, but also numerous circular features that suggest wind-driven mass accumulation and triggered star formation. Details of column densities and temperatures from these data are limited by the ~37" resolution of the 500 μm data. The addition of JCMT data at 450 μm and 850 μm would improve the resolution of such data by a factor of ~2.*

Most star formation within the Milky Way occurs in giant molecular clouds (GMCs) distributed within the Galactic Plane. In particular, examples of high-mass star formation are found exclusively there. Hence, the Galactic Plane has been a preferred target of large-scale surveys of young, massive stars and the interstellar medium (e.g., GLIMPSE with Spitzer). Most recently, the Herschel Space Observatory was used by the Hi-GAL consortium to map most of the Galactic Plane at $|b| < 1^\circ$ at 70-500 μm (in 5 specific wavebands; see Figure 12). Hi-GAL is producing spectacular images that reveal much about the large-scale structures of GMCs and the stars that form within them. For example, Hi-GAL has identified the predominance of filamentary structures threading the Plane. A major issue affecting interpretation of Hi-GAL data, however, has been source confusion due to low resolution. As the Herschel beam enlarges to ~37" at 500 μm, objects seen distinctly at shorter wavelengths blend, and it is difficult to assign longer wavelength fluxes to such objects given possible differences in temperature and dust opacity. Since Galactic Plane GMCs can be several kiloparsecs distant, linear resolutions of column density or temperature maps from Hi-GAL can be 0.1-1 pc, or worse.

The JCMT Galactic Plane Legacy Survey (JPS) will help source confusion by using SCUBA-2 to map areas of the Galactic Plane within $|b| < 1^\circ$. It is unclear at present how much of the Galactic Plane it will be possible to cover with SCUBA-2 and to what sensitivity; a re-scoping exercise of the JPS is currently in process. With a new, larger-format continuum array, however, JCMT will be able to image the Galactic Plane far better than possible with SCUBA-2. The science case for these surveys remains strong; JCMT’s spatial resolutions at 850 μm and 450 μm are nearly matched to those of Herschel at 250 μm and 160 μm. Inclusion of such JCMT data in spectral energy distributions (SEDs) would improve the resolution of Galactic Plane column density and temperature maps by factors of ~2. In particular, this new continuum instrument could allow for much wider Galactic

Plane coverage to better sensitivities than JPS and possibly Hi-GAL, reducing confusion, yielding more information about the wider Plane, and revealing sources not previously identified in the far-infrared and submillimetre due to low resolution. Furthermore, Galactic Plane sources would be detected at JCMT at wavelengths much better suited for planning follow-up higher angular resolution observations with ALMA.

2.2 Large-Scale Studies of Magnetic Fields through Dust Polarization

The role of magnetic fields in the formation of clouds and cores (and thus stars) has been debated widely over the past two decades. What is clear is that magnetic fields should influence how these structures form and evolve if they are present, given the not insignificant ionization fractions that have been measured in clouds. Data about the magnetic field strengths, a key indicator of their relevance, have been scant, however, mostly because such data can be very difficult to obtain (e.g., Zeeman line splitting is hard to measure and interpret). More commonly, magnetic fields have been probed using the polarization of thermal emission from dust grains. Indeed, SCUBA at JCMT was a world-leader in measuring the directions of magnetic fields using the polarization of thermal emission from dust grains. Such polarization data can be used in principle to estimate roughly field strengths, e.g., using the Chandrasekhar-Fermi (CF) method with approximations. A drawback of this method is that data of lines emitted from the same locations as the polarized flux are needed as inputs.

A promising new technique has been recently proposed to measure the magnitudes of ordered and turbulent magnetic field components with fewer assumptions than the CF method. This technique requires the acquisition of hundreds of vectors across a region to measure the characteristic scale of turbulence within clouds based on an angular dispersion function. Such data were difficult to obtain with SCUBA and may be also difficult even with SCUBA-2. A new large-format bolometric array combined with a polarimeter, or even a dedicated polarimeter allowing simultaneous detection of orthogonal polarization, would allow effective studies of the magnitude of the magnetic field using wide-field polarization surveys. The advantages here are twofold: first, the new polarimeter would allow much wider fields to be surveyed for polarization, and second, it would allow much deeper observations to detect polarization fluxes that are typically only a few percent of the observed continuum brightness. Such data of large-scale magnetic fields within nearby molecular clouds (and the Galactic Plane) may be a unique contribution by JCMT to understanding the physics of the interstellar medium, in the absence of other large-format polarimeters in the foreseeable future.

2.3 Time-Domain Submillimetre Photometry

Submillimetre photometry of galactic sources has been treated historically without any consideration of the possible time variability of such emission. Monitoring variability at submillimetre wavelengths from the ground is indeed intrinsically difficult because of the variable nature of the atmosphere and the imperfect cancellations that result when both targets and calibrators are observed. For this reason, standard uncertainties of 850 μm and 450 μm flux measurements with SCUBA were typically ~20% and ~50% respectively, unless extremely careful calibration procedures were followed. Such large uncertainties, however, could mask real variations of source fluxes. For example, the submillimetre fluxes of protostellar cores (e.g., FU Ori and EX Ori stars) could vary significantly due to accretion-related events that vary the UV fluxes of embedded protostars. Such emission would propagate through the surrounding envelope via reprocessing by dust grains and be emitted as variable submillimetre flux. Indeed, such submillimetre variations, if caught and monitored with sufficiently high cadence, could then conceivably constrain the density profiles of protostellar envelopes. A difficulty with using such a probe toward any single target, however, is the unpredictable nature of UV variability due to irregularities of accretion flows, making it observationally expensive to monitor a sample of sources for variability. Nevertheless, a submillimetre "flare" was detected serendipitously at JCMT towards GG Tau (see Figure 13).

A new, large-format, sensitive continuum instrument at the JCMT would make monitoring variability through time-domain submillimetre photometry finally possible. Such an instrument would have a large enough instantaneous FOV (e.g., 30′) to allow several protostellar cores (e.g., in a clustered star-forming region like Orion) to be imaged near-simultaneously within the same footprint or small area. The high intrinsic sensitivity of the instrument would allow a large population to be detected at once, capturing a single epoch in a relatively short amount of integration time. Such an instrument therefore makes monitoring for variability quite observationally inexpensive because now many regions (and objects) can be easily sampled over several epochs. Observing near-simultaneously several sources within a single field also improves the ability to detect variability. For example, repeated visits to rich fields would eventually provide robust photometric baselines from which significant relative flux deviations of individual objects could be seen. Such monitoring observations could be undertaken with SCUBA-2 but its relatively small 8′ FOV footprint severely limits the number of regions (and objects) that can be observed repeatedly, lowering the possibility of detecting variability.

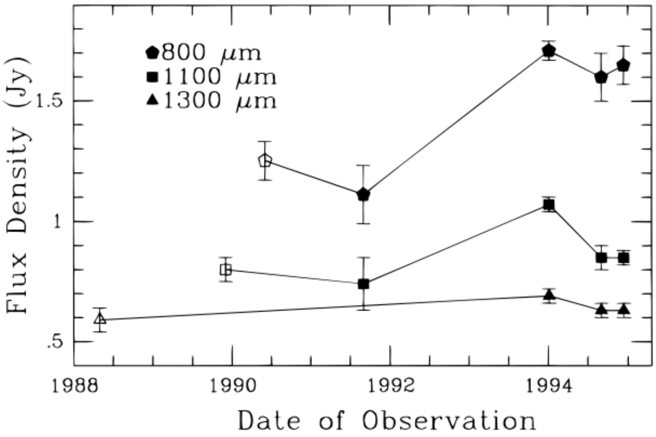


Figure Thirteen: *Changes in the submillimetre fluxes of the young star GG Tau, as observed from JCMT with UKT14 (!) by Moriarty-Schieven & Butner (1997). The significant increases in flux densities seen, in early 1994, especially at 800 μm, demonstrate that significant variability does indeed occur and can be detected in the submillimetre wavebands. A new, large-format continuum instrument at the JCMT will be able to monitor several young targets with much greater temporal sampling rates, allowing investigations of time-dependent phenomena at such wavelengths for the first time*

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2.3 Deep Surveys of the Outer Regions of Nearby Molecular Clouds

Molecular clouds form stars in their deepest, high-extinction interiors. Such regions only account for small percentages of the sizes and masses of molecular material in these clouds, however. The key to understanding the formation of clouds themselves may lie in sensitive observations of their diffuse outermost extents. The outermost extents of clouds, where HI is converted to H_2 (and vice-versa) are difficult to probe. H_2 is not an easy molecule to observe, and the molecule typically used as its surrogate, CO, is not found in high abundance at low extinctions ($A_V < 1$) due to dissociation by the ISRF. In theory, outer cloud regions and the transition from molecular clouds to atomic halos could be probed using their dust. Indeed, some preliminary IR work has detected "cloudshine," the external illumination of clouds by the ISRF on dust. Also, wide-field optical/IR extinction maps in principle probe such outer regions but these data typically have very low angular resolution, e.g., 1-10′; see Figure 14. On the other hand, dust in outer cloud regions could be traced by the faint, extended thermal emission it emits. This emission, however, has not been studied extensively before, given the need for sensitive wide-field instrumentation that retains large-scale structure. Molecular clouds are not being presently well studied at their low extinctions with Herschel, beyond perhaps observations of distant clouds with Hi-GAL at low linear resolutions.

A new, large-format continuum instrument on JCMT has the potential to explore the exteriors of nearby molecular clouds at high linear resolution, a relatively unexamined aspect of the interstellar medium. Assuming a 30′ FOV, such an instrument could map the large peripheries of nearby clouds, looking for faint, extended emission from dust there. The key here is that dust at such locations is more directly illuminated by the ISRF and should then be warmer, e.g., >20-40 K, than cold dust in the deeper cloud interiors, allowing the lower column densities at the cloud peripheries to be probed. Such observations will be still quite challenging; assuming T = 40 K and typical dust properties, we estimate an 850 μm flux of ~10 mJy from dust at Av = 1. Given that ground-based observations may be limited to detecting structures on scales up to the FOV of the array, structures within this diffuse component may be detectible only with a large-format instrument. Though admittedly speculative, such projects could open a new frontier in understanding molecular cloud formation and evolution.

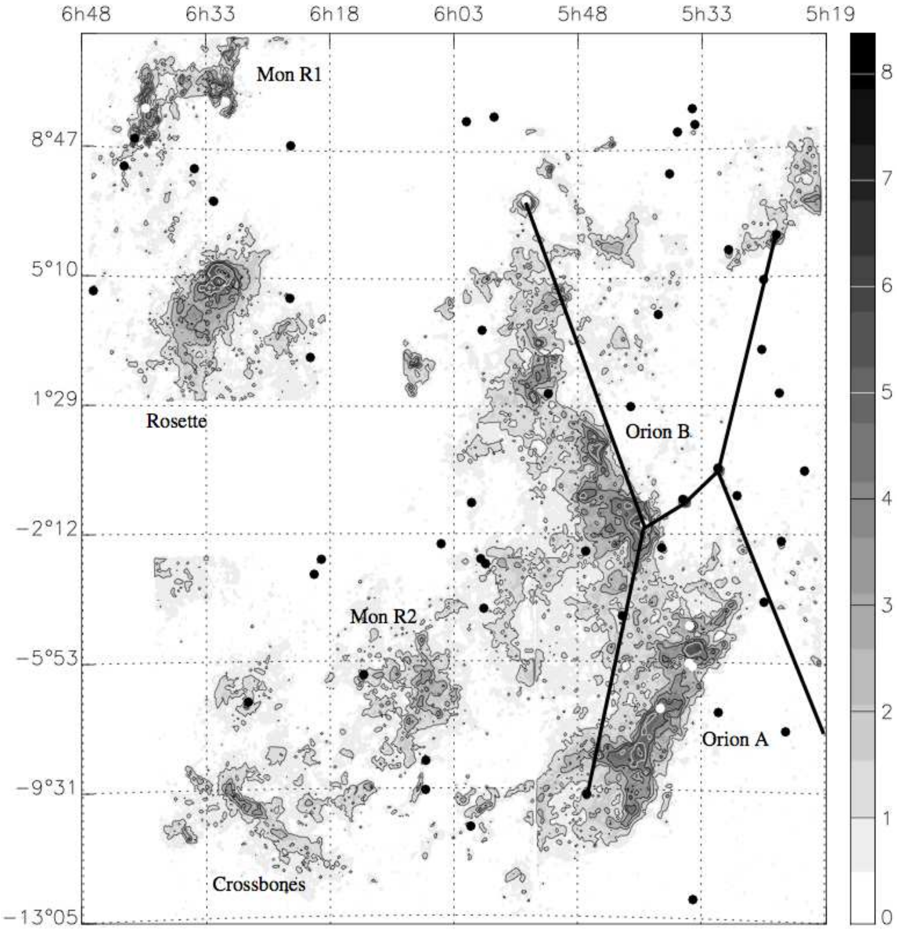

Figure Fourteen: *A wide-field extinction map of the Orion, Rosette, Monoceros, and Crossbones molecular clouds by Cambrésy (1999), made using star-counts in the R band. Spatial resolutions are typically 1' in the outer parts of the cloud to 10' in the inner parts of the cloud. Submillimetre continuum surveys could sample the outer parts of the cloud to higher angular resolutions than shown above, yet these have not been the focus of such surveys of clouds in the past, mostly because their diffuse nature is difficult to capture with relatively small FOV continuum instruments. A new, large-format continuum instrument (e.g., with a 30' FOV) would allow such studies to occur.*

5: Instrument Procurement Model

The original model for JCMT instrument procurement was based on the concept of “well-found laboratories” in each of the partner countries that would do R&D and build instruments for the telescope, with the partner countries funding the staff and non-deliverable costs. Historically this was very effective in equipping JCMT with world-leading instruments such as SCUBA and all the heterodyne receivers. SCUBA-2, on the other hand was built on a “full-costs” basis but at a very high cost to the partners. This model is clearly not sustainable in the 2020 era given the financial constraints in the partners.

The panel recommends a different model based on that used, also very successfully by the IRAM 30M telescope, in the past to acquire the MAMBO camera for example . In this model the telescope assesses its science needs and possible technical solutions, possibly in collaboration with other groups who may wish to mount a PI instrument on the telescope in order to demonstrate possible solutions. The telescope management makes an assessment of what it might cost to build such an instrument, both in terms of deliverable hardware and staff time, and what it is prepared (or can afford to) pay. The telescope then issues an announcement of opportunity to bid to build the instrument on the basis of a fixed contribution to the hardware costs with the builders covering staff costs, and in return receiving a substantial block of guaranteed telescope time. An example of such an announcement is appended to this report.

The panel strongly recommends that JCMT Board switch to such a procurement model as the only likely viable route to obtain the world-class instruments suggested in this report. For example if the JCMT operation was extended to 2020 and the FOV enlarged, then a larger-format camera could be procured on the basis of, say, a £1M contribution towards hardware costs and 1000 hours of observing time to the successful bidders.

Acknowledgements
The panel thanks Doug Johnstone, Holly Thomas, Martin Houde and Helen Kirk who made helpful comments on the galactic science section, and Steve Eales, Phil Mauskopf and Jon Davies for their help on the extragalactic section.

Annexes

Annex One: Terms of reference and panel membership

Annex Two: Report on optical design study by David Henry

Annex Three: Report on design study for JCMT surface upgrade, by EIE

Annex Four: Recent Announcement of Opportunity to bid to build a large-format camera for IRAM.

November 27th 2011