COMMON-USER SUBMILLIMETRE BOLOMETER ARRAY - 2

SCUBA2

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1. Introduction

This document describes the science case for the development of a medium resolution Fourier transform spectrometer (FTS) for SCUBA-2. The scientific aims of the FTS seek to capitalize on the imaging power and sensitivity of the SCUBA-2 camera, and extend its capabilities to include medium resolution imaging spectroscopy across the 450 and 850 μm atmospheric windows. New kinds of targets and surveys that are currently not feasible with single pixel spectrometers will become possible with the introduction of the SCUBA-2 FTS. Since the spectral resolution of the FTS can be adjusted instantly, the resolution can be optimized for the scientific problem at hand. Examples of three areas of interest are given below, in no particular order:

2. Extragalactic astronomy

The extragalactic submillimetre community is engaged in projects that require some understanding of the Spectral Energy Distribution (SED) of the dust emission from Ultra-Luminous Infra-Red Galaxies (ULIRGs). Unfortunately, our knowledge is limited to only a handful of photometric measurements in even the best studied bright sources. In particular, the dust emissivity is determined essentially by fitting a line between fluxes measured with SCUBA at 450 and 850 μm. The problem with this approach is that 450 μm observations are typically difficult to obtain and calibrate, and the 850 μm fluxes have a non-negligible contamination from CO line emission. Also, the assumption used in these fits is that the SED is dominated by a single dust temperature/emissivity, which in many cases is known to be wrong. By using an FTS to measure the SED across a long wavelength band, one can escape these issues and determine the emissivity directly.

An early, groundbreaking result from SCUBA was the measurement of 104 nearby Luminous Infrared Galaxies (LIRGs) detected by IRAS. By using the 60, 100, and 850 micron fluxes, along with a simple model for the shape of the dust SEDs, Dunne et al.[1] fit the temperature and dust emissivities of the sources. The SEDs of this Scuba Local Universe and Galaxy Survey (SLUGS) sample are now used in photometric redshift estimators for the more distant ULIRG population ($z > 1$).[2,3] However, it is now clear that using continuum measurements alone can bias the fits. In particular, recent heterodyne observations of this sample by Yao et al.[4] reveal that a significant fraction of the continuum flux measured by SCUBA at 850 μm is, in fact, due to CO 3-2 line emission. Also, there is more and more evidence that ULIRG SEDs are better fit by using multi-temperature models. This is revealed in part by 450 μm observations of 17 of the SLUGS.[5] At these shorter wavelengths, the strength of the emission is particularly sensitive to the SED model, as it is near the peak of the thermal emission. Heterodyne observations of these galaxies are useful for charactering their line emission, but their narrow bandwidth means that little can be learned about the shape of the underlying continuum. This is where a low resolution, broadband spectroscopic observation can be particularly useful. With the SCUBA-2 FTS it will be possible to simultaneously measure the slope of the dust emissivity across both the 450 and 850 μm bands. Obtaining this information in both bands is particularly useful since the short wavelength observations, in addition to being substantially more difficult due to the poor atmospheric transmission and stability, are near the thermal peak of the SED, and hence more difficult to interpret.

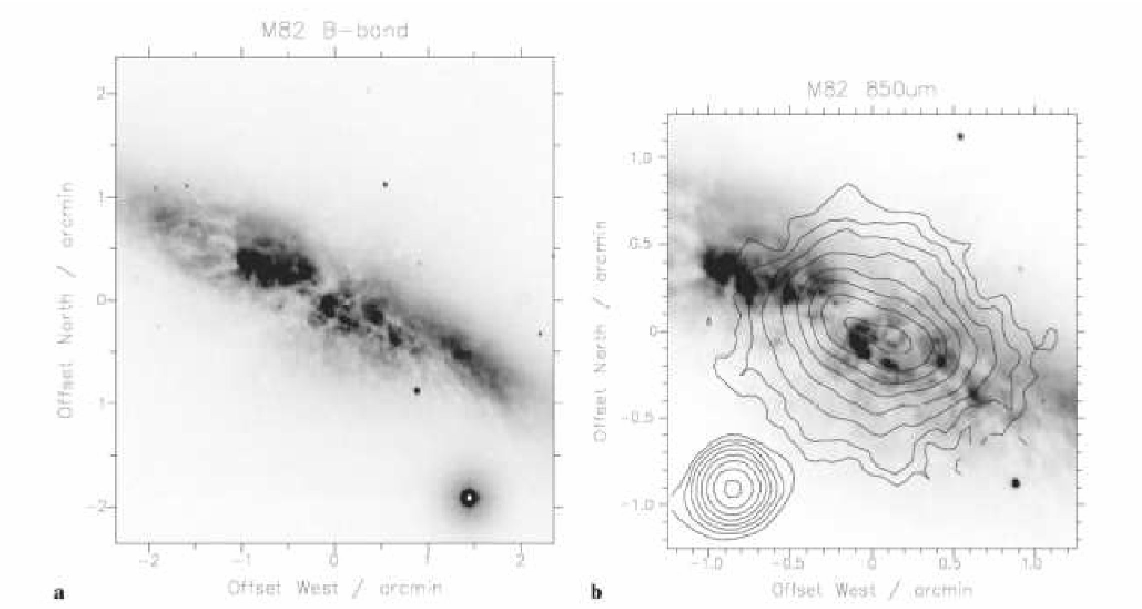

Figure 1. M82 as seen by SCUBA at 850 μm. The panel on the left is simple the B-band optical image. On the right is a close-up of the central region, with SCUBA contours overlaid. The emission is clearly extended beyond the SCUBA beam, which is shown in the bottom left corner of the panel. (Figure taken from Alton et al. 1999 [6])

Table 1. Estimated FTS sensitivities.

	850 μm		450 μm	
Resolution (MHz)	150	3000	150	3000
Resolution (cm^{-1})	0.005	0.1	0.005	0.1
NEP (W/√Hz)	$8.5\cdot10^{-17}$	$8.5\cdot10^{-17}$	$\sim8\cdot10^{-16}$	$\sim8\cdot10^{-16}$
1-σ ΔT Sensitivity in one hour integration (mK)	2	0.1	~10	~1

By way of illustration, M82 is a nearby, well studied ULIRG, and is the brightest member of that class in the sky (Figure 1). With the estimated sensitivity given in Table 1 and using previous results from the CSO[7] it will be possible to obtain spectroscopic mapping of M82, at the highest spectral resolution of 150MHz, which will yield a S/N of 500 on the peak of the CO 3-2 line at 345GHz in an integration time of one hour.

3. Interstellar medium

One of the most important problems in modern astronomy is to understand the formation of stars and planets, which has implications for other branches of astronomy on all scales from galaxy formation to solar system formation. However, to understand the formation of stars we must first understand the detailed physics and chemistry of the interstellar medium (ISM). The ISM is where the material is collected together to form, first of all, dense clouds, and ultimately stars. There are many processes within these clouds that have a bearing on star formation. These include heating and cooling of the gas and dust, turbulent support and magnetic fields.

Since the general ISM is too hot to collapse to form stars, the cooling of gas clouds is of singular importance to star formation. This cooling process is complex and involves dust grains shielding the dense clouds from the general inter-stellar radiation field (ISRF), as well as cooling radiation from molecules and grains. Disentangling these different processes and understanding their complex interplay, and relative importance, is a significant problem. The SCUBA-2 FTS will attack this problem in several ways:

It will provide simultaneous measurements of both the continuum and line emission across the whole atmospheric windows at 450 and 850 μm at every point in a 16 square arcminute field of view (roughly one quarter of the SCUBA-2 field) at up to 150 MHz spectral resolution, and at the diffraction limited spatial resolution of the JCMT. This will provide a spectrum at every point in the image of a molecular cloud. Individual spectra can be analyzed to determine the total continuum flux and its spectral index, as well as detection of strong emission and absorption lines from many molecules that are playing a role in the radiative balance of the cloud. Such a data-cube will provide a unique resource, unmatched by any other facility on any other telescope. The spectral index variation across a cloud yields information on the variation of dust grain properties such as temperature, optical depth and grain emissivity. The latter embodies information on dust grain growth and dust destruction. The detection of molecular lines will pave the way for high resolution observations with instruments such as HARP.

Simultaneous mapping of dust emission and spectral index together with molecular line detection from significant molecules, such as CO, CS, OH, HCN, HCO+, etc., and major isotopomers of these lines, will provide an extremely powerful set of diagnostics of the physics and chemistry of the molecular cloud region being studied. For example, any significant bipolar outflows in the cloud will be visible in the main CO lines. These can be relatively wide and hence contain significant flux that would otherwise contaminate continuum measurements made without a spectrometer.

The variation in relative line strengths from one molecular species to another yields detailed information on the chemistry of a region. The first step in the chemistry of the ISM is believed to be the formation of molecular Hydrogen from atomic Hydrogen on the surfaces of dust grains. Thereafter the molecular Hydrogen is released back into the gas phase, where it participates in what is now known to be a rich chemistry. In general, ionneutral reactions proceed faster than neutral-neutral reactions, and the primary reactions are believed to be initiated by cosmic rays (cr):

$$H2 + cr \rightarrow H2^{+} + e^{-}$$

$$H2^{+} + H2 \rightarrow H3^{+} + H$$

$$H3^{+} + O \rightarrow OH^{+} + H2$$

Thereafter the OH+ drives the oxygen chemistry. A similar sequence occurs for the carbon chemistry. There are now known to be some 120 molecular species that have been identified in space, up to about 13 atoms in size. To build a chemistry that explains their existence a number of chemical models of networks containing some 400 species interacting in about 4000 chemical reactions have been developed. An understanding of these reactions is central to the interpretation of molecular chemistry in the ISM.

Producing a map of such a molecular cloud in one or two molecular line tracers is currently a slow process. Furthermore, the resultant map does not simply trace gas density, since a given species can be formed and destroyed by different chemical reactions in different parts of a cloud, and variations in the intensity of a single spectral line could therefore simply be mapping variations in the chemical processes across a cloud. Furthermore, molecules can be frozen out of the gas phase onto the surfaces of dust grains in regions of high density and low temperature. Thus in the very regions most likely to form stars, single molecular line tracers can suddenly appear to decrease in column density.

Likewise, the mapping of the continuum emission across a cloud, whilst being a tracer of the dust density, is also complicated by variations in dust grain parameters. Hence a single waveband SCUBA continuum image traces a combination of density, temperature, grain emissivity and optical depth, all convolved in some fashion that is not easily disentangled. The SCUBA-2 FTS will allow these parameters to be separated from one another by providing a simultaneous line and continuum spectrum across an entire waveband at every point in a molecular cloud. Indeed, recent measurements obtained with the University of Lethbridge FTS operating with a single detector at the JCMT have shown that Fourier spectroscopy is capable of differentiating continuum and line emission in complex regions like the Orion molecular cloud, although only at discrete locations.

To date, theoretical modeling of the ISM has outpaced observations. There are complex theoretical chemical codes available that include the reaction rates for a few thousand chemical reactions. There are radiative transfer codes that can predict the observed molecular line intensities across a molecular cloud for any of several hundred molecular lines. What is required now is a set of large data-cubes covering many lines and the continuum across many different molecular cloud regions to allow a detailed comparison between models and observations, and to differentiate between the many theoretical models that currently exist.

The SCUBA-2 FTS will provide just such a series of datasets. It will allow observers to calculate detailed abundances of many important molecular species as a function of position in the cloud. From these data it will be possible to calculate where specific molecular lines have become optically thick, and where molecular species are being depleted due to chemical reactions. It will also be possible to determine those locations where molecules are being frozen out onto dust grains due to increased density and a decrease in temperature.

In short, the SCUBA-2 FTS will give an instantaneous snapshot of the primary physical and chemical parameters across a molecular cloud. This will provide a significant step forward in our understanding of the physical conditions of star forming regions.

4. Planetary Atmospheres

The submillimetre region is a particularly rich field of study because it is the region of maximum intensity for the rotational lines of many potential atmospheric constituents. Spectroscopic measurements provide an inventory of molecular species and information on the physical and dynamical processes (e.g. internal heat sources) of the atmosphere. Observations of the giant planets also provide an important database for calibrating astronomical sources. With its broad spectral coverage and intermediate resolution, an FTS is ideally suited to measuring the pressure broadened tropospheric absorption features in planetary atmospheres.

It is evident that current theoretical models do not describe well the observed spectra of the giant planets at submillimetre and far-infrared wavelengths. For example, reported brightness temperature measurements of Jupiter differ significantly in the region from 350 to 500 µm.[8,9,10] Although these measurements are photometric, attempts have been made to compare the results with theoretical models of the Jovian atmosphere. The principle sources of atmospheric absorption: pressure induced absorption of H_2-H_2, H_2-He; gaseous absorption of NH_3, PH_3, CO and NH_3 cloud particles, are found to be insufficient to explain the observed results. Model spectra of the giant planets at submillimetre wavelengths have revealed a plethora of lines arising from NH_3, PH_3, HCN and CO, and a wide range of non-equilibrium species.[11] The detectability of such molecular species from their rotational transitions has been addressed by Encrenaz.[12]

Recent measurements of the submillimetre spectra of Jupiter and Saturn[13] yielded three results: first, detection of the PH_3 $3\rightarrow2$ transition in both planets; second, a tentative detection of the HCI $1\rightarrow0$ transition in Saturn (though not in Jupiter); and third, non-detection of a number other halides, including HBr, LiH, NaH, HCN and HCP (see Figure 2). The detection of HCI is surprising since chlorine is a trace constituent in solar-composition objects. The atmospheres of both planets are highly convective, due to their internal heat sources, and as the gas rises from the hot deep interior and cools, HCl should react with gaseous ammonia (plentiful by comparison) and condense to form solid

NH_4Cl particles.[14] This occurs well below detectable levels, at a pressure of ~ 20 bar: the tenuous cloud layer formed by this process is not visible to telescopic observations due to the presence of three thicker overlying layers (H_2O, NH_4SH and NH_3).

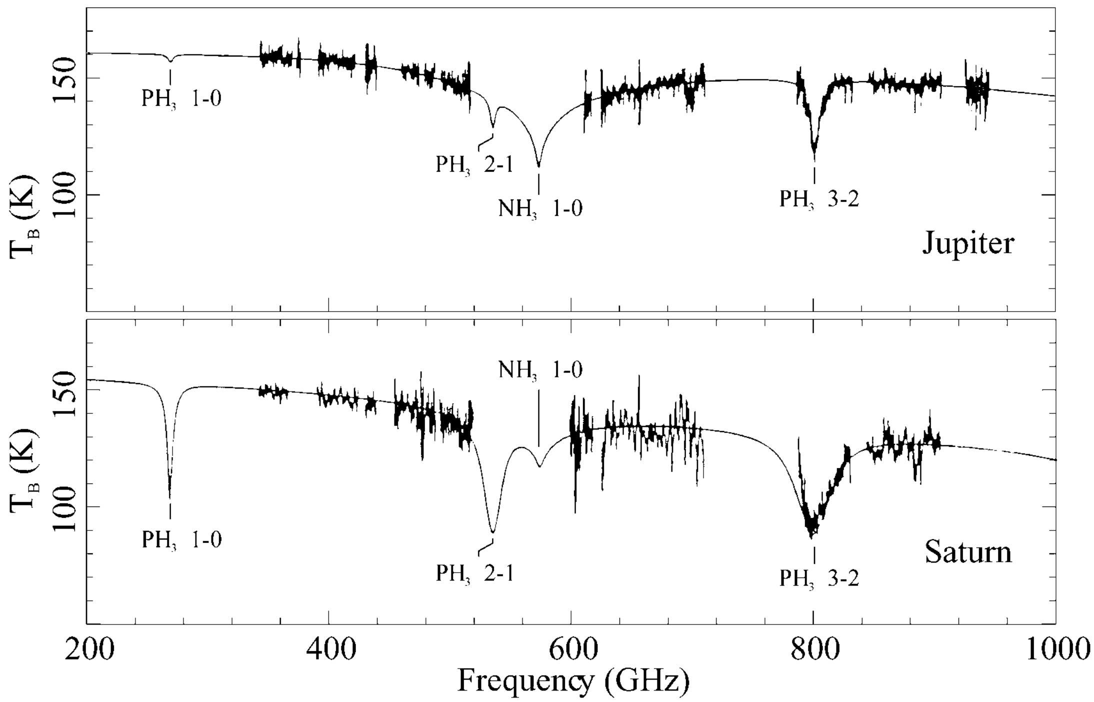

Figure 2. Submillimetre spectra of Jupiter and Saturn[13]

The only mechanism by which HCl could evade condensation and exist in the upper troposphere is if the vertical transport is significantly faster than the chemical equilibration lifetime. This is the same mechanism by which phosphine reaches observable levels, and the detection of PH_3 at submillimetre[13] and infrared wavelengths, in both Jupiter and Saturn attest to the strength of the convection. On the other hand, the absence of H_2S at observable levels serves as a counter-example: this gas is more abundant than HCl but condenses thoroughly to NH_4SH and has never been detected. Recent analysis of the Galileo Probe Mass Spectrometer (GPMS) data has resulted in a tentative detection of HCl [15] (although the GPMS sampled a point location on the planet which may be unrepresentative of the global emission). Bezard *et al.* have shown that all of the hydrogen halides are potentially detectable at submillimetre wavelengths.[11]

The increased sensitivity of the SCUBA-2 FTS and small diffraction limited JCMT beam of 7” at 450 micron will allow, for the first time, submillimetre spectral mapping of the Jovian, Saturnian and Martian discs (which have angular sizes of 45”, 19” and 16”, respectively at opposition) and the study of hemispheric, zonal and polar differences and transport effects. Spectral mapping of Jupiter will also be practical at longer wavelengths where the diffraction limit reaches 14” at 850 micron.

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