SCOWL – taking OWL into the submillimetre

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Abstract: SCOWL[1] is a concept for a wide-field sub-mm camera for the OWL telescope. The instrument will be up to an order of magnitude more sensitive per pixel and many orders of magnitude faster at widefield mapping than other facilities available in the next decade. It will significantly broaden the scientific capabilities of OWL. For example, it will be possible to detect cool dust in debris discs like our own Solar System out to 20pc, or detect normal Galaxies like our Milky Way throughout most of the Universe. It will provide a pathfinder for detailed followup with ALMA. In the following, we summarise the science case together with an outline conceptual design, and the predicted capabilities. We show the performance of SCOWL on different sites and with different telescope apertures; major science gains will be realized on a 50m+ telescope on a suitably dry site.

Keywords: submillimetre, bolometer, array

1. SUBMILLIMETRE SCIENCE

Emission at submillimetre wavelengths is most sensitive to cool dust and gas, with for example the blackbody radiation from a 10K source (or a 40K source at a redshift of 3) peaking at ~300µm. As a consequence, the main area of submillimetre astronomy is the study of *formation* processes, be it of planets, stars or galaxies. Sites of formation of these most fundamental structures are generally cool, rich in dust, and hidden by many magnitudes of visual extinction; consequently most of their energy is emitted in the 30-3000µm region. An additional important feature of the submillimetre continuum emission from dust is that in nearly all situations the emission is optically thin; this ensures that observations probe right to the heart of the most crucial processes and trace emission over a very wide dynamic range of density and mass. In the following sections we outline some of the key science questions that would be addressed by an instrument with the capabilities of SCOWL.

1.1. Why is the Solar System so free of dust: do we live in an unusual planetary system?

Debris discs are the result of collisions and grinding down of asteroids around main-sequence stars. Most images have been obtained in the submillimetre, but so far we have only been able to study the very dustiest examples. For the first time, *SCOWL will enable us to detect debris systems with dust masses similar to our Solar System*, around stars to 20pc (Figure 1). This will not be possible with proposed far-infrared missions over the next ~20 years because of their large beams and consequent confusion by the bright stellar photospheric emission. SCOWL can investigate dust-free planetary systems, possibly the best targets for life-bearing planets, influencing the target selection for deep searches for thermal emission from Terrestrial Planets. The Planet Finder capability of other OWL instruments combined with SCOWL will allow us to investigate the complete range of rocky bodies around nearby stars, from giant planets down to dust grains.

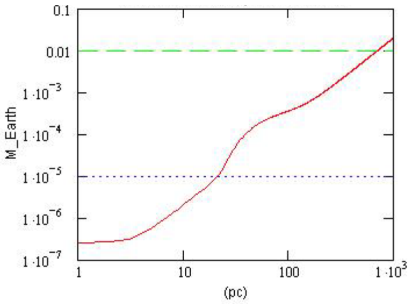

Figure 1: Dust mass detectable (10σ, in Earth masses) by SCOWL at 450µm around a Solar-type star as a function of distance (solid line). Upper dashed line represents the dust mass around ε Eri, and lower dotted line that of our own Solar System.

1.2. How do the lowest and highest mass stars form?

Existing surveys suggest that the stellar IMF may be controlled by the pre-stellar clump mass spectrum; however, even in the closest regions, they are incomplete below 0.1 Solar mass. The mass sensitivity limit of SCOWL can be translated to a 10σ detection of a 0.1 Jupiter mass clump in a 1 degree survey of Orion. It would therefore be able to study the formation of the lowest mass stars or even “free-floating” planets.

The early stages of *high*-mass star formation are also very poorly understood, partly because there are fewer high-mass stars, but also because the formation process is so fast and consequently rare. This is important to understand, because of the significant affect they have on the large-scale ISM. SCOWL would allow a full census of *all* high-mass star formation throughout the Galaxy, showing the rarest of phases, and allow us to understand what defines the high-mass end of the stellar IMF.

1.3. Where is the bulk of dust in Galaxies? Is there an additional “cold, dark” massive component?

The only reliable way to trace the bulk of dust in galaxies is through submillimetre imaging. Dust in spirals is detected in extreme cold (<15K), low-surface brightness disks often extended far from the nucleus. Such cold dust radiates strongly in the submillimetre and is faint already in the far infrared. *In many galaxies this component dominates the total dust mass*. How far such dust extends beyond the disc is unclear: does it extend to the intergalactic medium? Is it distributed in galaxy clusters or present in cooling flows? How much does it contribute to the rotation curve and is there a relation to cold dark matter in Galaxies? High-sensitivity large-scale submillimetre mapping is the only way to answer these questions.

1.4. The origin of dust.

Despite the importance of dust in the interstellar medium, it is still unclear whether it forms mostly in supernovae remnants or in evolved stars. Most SNR are too large and have too low surface brightness to be studied with current facilities. Equally the episodic violent ejections from evolved stars produce highly-extended rings of emission. High resolution imaging of arcminute fields is required to trace either phenomenon. This will allow us to verify masses, ejection time scales, production rates and also clumping.

1.5. What is the star formation history of the Universe? Detecting “normal” Galaxies to the edge of the Universe.

The existence of submillimetre (or “SCUBA”) galaxies has changed our view of Galaxy evolution. But currently we can only detect the very brightest “monsters” at high redshifts, with extreme star formation rates of ~10^3 Solar masses per year, 1000 times that of the Milky Way. SCOWL could map the field of view and detect objects ~1000x fainter at 850μm in ~50 hours, reaching well below the confusion limitations of the next decade of deep far-infrared or submillimetre surveys. Such a project would resolve almost all the submillimetre background flux. The negative K-correction for dust emission in the submillimetre means that a galaxy like the Milky Way would have an 850μm flux of ~10μJy if observed at *any* redshift between 1 and 10. *SCOWL would therefore be able to detect normal Galaxies like the Milky Way throughout the Universe*.

SCOWL will be ideal for very large-scale surveys of star formation in the deep Universe: for example it will detect more than 10^5 objects over 1 square degree in a 100-hour mapping project. The 850, 450 and 350μm bands are ideally placed for measuring photometric redshifts from z=1-10. Such a survey will provide photometric redshifts for all 10^5 objects, tracing star formation in three dimensions.

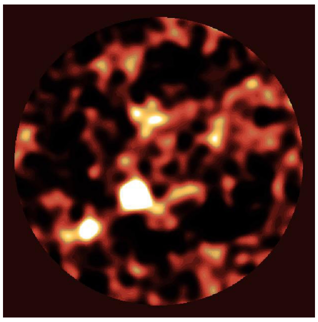

Figure 2: SCUBA image of the Hubble Deep Field, approximately 2 arcmin on a side[2]. SCOWL will provide maps an order of magnitude deeper than this, over *1 square degree*, with ~10 times better resolution.

2. CONCEPTUAL DESIGN

The baseline design of SCOWL uses the same approach as SCUBA-2[3], currently at the cutting edge of submillimetre continuum camera design. This is currently regarded as the lowest risk approach, and uses 48 of the existing TES detector arrays with a total of ~20000 pixels at each wavelength. The instrument layout is shown below. The cryostat volume would be ~24m^3, with a total weight of 6 tonnes.

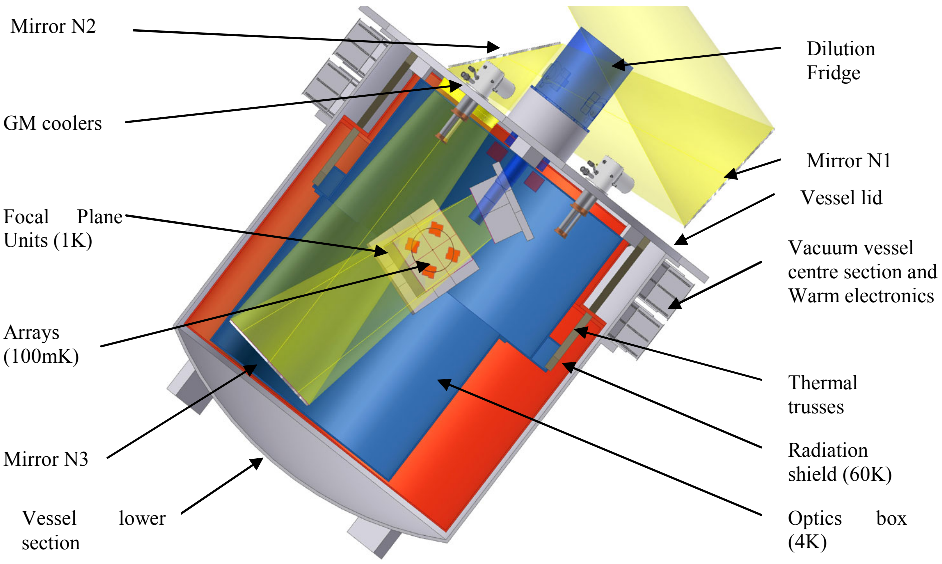

Figure 3: SCOWL cryostat layout. Only one of the 3 focal plane arrays is shown for clarity. The cryostat would be ~2m in length.

2.1. Technical issues

A significant amount of cooling power will be required to operate SCOWL, including stages at 60, 4 and 1K, and the detectors themselves at 100mK. The dilution fridges currently used for SCUBA-2 will not operate effectively when tipped, and development will be required to solve this. Although we have assumed SCOWL would use TES detector arrays similar to SCUBA-2, the number of readout wires required will be in excess of 20,000, resulting in a large heat load on the 100mK stage. Furthermore the SQUID readouts and electronics limit the TES array packing density, with the result that only ~30% of the field of view would be paved by detectors. Alternative detector technologies such as KIDs may have significant advantages for large-format submillimetre arrays like SCOWL, and need to be investigated further. Their wafer design is much simpler, which should result in easier manufacture and scalability, and they can be frequency-multiplexed, resulting in a much lower readout wire count. The disadvantages of KIDs are the more complex room-temperature demultiplexing, potential difficulties with coupling to the beam pattern for a Nyquist-sampled array, and the R & D required to prove their worth.

Other technical issues that arose from the SCOWL investigation were the potential difficulties in manufacturing the large optics (in particular in the size of submillimetre windows, dichroics, filters and waveplates), possible problems with instrument flexure on OWL, and the need to correct for submillimetre "seeing" (where the beam is affected by passing clumps of water vapour). Given the submillimetre background number counts (see section 4), and the field of view and sensitivity of SCOWL, there are likely to be 1-2 background objects in the field of view which could be detected at 10σ in 1 second. It is proposed that these would be used to measure and remove the effects of slow instrument flexure and submillimetre tip-tilt corrections for the "seeing". Data from the arrays will be read out and stored at ~200Hz, and so these "guide-galaxies" could be used in the data reduction stage.

Clearly time on the OWL telescope will be at a premium (and SCOWL will be competing with a lot of optical astronomers!), so the issue of operation during twilight or even daytime needs further investigation, as do alternatives such as a hitchhiker mode, where OWL can be used simultaneously in the optical/infrared as well as the submillimetre. This will maximize the scientific return on the telescope investment.

3. INSTRUMENT PERFORMANCE AND COMPARISON WITH OTHER FACILITIES

The basic design goal of SCOWL is to pave a large fraction of the telescope science field of view with Nyquist-sampled pixels having sky-limited sensitivity at all three primary submillimetre wavebands. To this three-band simultaneous imaging, SCOWL will also include a polarimetric capability. The huge OWL collecting area (effectively larger than ALMA) and high detector sensitivity means it will be possible to image objects around the 10µJy level at 850µm, more than two orders of magnitude better than existing instruments. The beam is sufficiently small that confusion noise from high-redshift galaxies and local galactic cirrus over most of the sky is at the level of a few µJy. At the shorter wavelengths, assuming a precipitable water vapor (pwv) content above the OWL site of 0.5-1 mm, a point-source sensitivity of 100-200µJy (10σ/1hr) at 450µm will be reached; for comparison, current instruments struggle to detect sources below 100*mJy* at this wavelength. Based on the design outlined above, we list below some of the key capabilities of SCOWL.

Table 1: SCOWL performance

Parameter	Performance	Notes
Wavelengths	850, 450, 350µm (simultaneously)	Set by atmospheric windows
Sensitivity	50µJy at 850µm (100µJy at 450µm)	10σ, 1hr, per pixel
Beamsize	1-2 arcsec	Diffraction-limited
No. of pixels	≥10,000 – 20,000 per wavelength	Depends on detector technology
Field of view	2.5 x 2.5 arcmin	Set by telescope design
Mapping sensitivity	2-10mJy per square degree per hour	10σ, fully-sampled map

3.1. Comparison with other facilities

In the chart below we compare relative sensitivities *per pixel* to a given dust mass, for SCOWL and other mm/submm facilities in the next decade. These numbers assume dust emission spectral index of α=3 at z<1. They illustrate that even if SCOWL had only one pixel, it would be between 3 and 10 times more sensitive than any other facility. However, the area where SCOWL would really stand out would be widefield mapping. ALMA will clearly be the facility of choice for high resolution studies in the next decade. But for example, SCOWL at 850µm could map 1 square degree down to 1σ=30µJy within 4 observing nights, while ALMA even if it were possible would need 20,000yr! Observing large areas of sky in the submillimetre to high depths becomes feasible *only* with SCOWL. Furthermore at 1-2 arcsec, its' resolution would be intermediate between existing 15m-class telescopes and ALMA. As such, SCOWL would act as a pathfinder, searching for new objects for high-resolution followup.

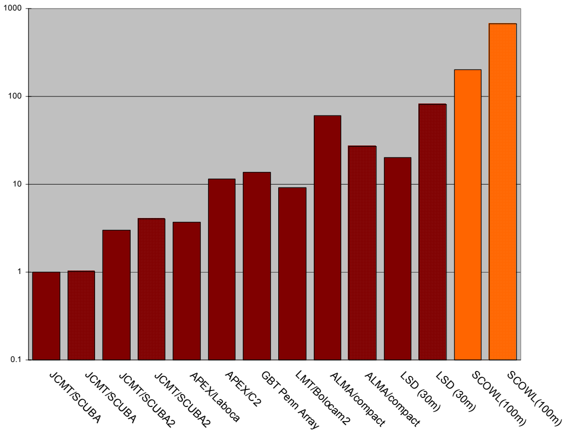

Figure 4: SCOWL relative sensitivity to dust mass, compared with other major facilities. Dotted bars represent 450µm.

4. SENSITIVITY AND CONFUSION: THE EFFECTS OF TELESCOPE APERTURE AND SITE

To first order, the sensitivity of an instrument such as SCOWL depends on the aperture D^2, giving projected sensitivities for different telescope concepts in the following table. However, perhaps a more critical issue for submillimetre widefield instruments is confusion from other sources, most commonly background galaxies [4] or extended Galactic cirrus [5]. The former is, to first order, isotropic; however, Galaxy clustering and lensing can raise the confusion limit locally by a factor of a few. Deep number counts are very uncertain; we have used ones based on recent extrapolations of submillimetre data and evolutionary models [6]. However, there is likely to be a factor of 2-3 uncertainty in these values. In the table below we give the 1 source/30 beams limit, a commonly-used measure of confusion. Also we give the time to reach this level (at 10σ detection) in a single-pixel photometric observation; for mapping this would be scaled by the filling factor of the field of view and required map size. For comparison the Galactic cirrus level over 90% of the sky is ≤6μJy and ≤12μJy per beam at 850 and 450μm respectively (for a 100m aperture). This table illustrates the point that the predicted number count slopes means the confusion limit drops rapidly for apertures larger than 50m. But it should be noted that these predictions are model-dependent.

Telescope aperture D (m)	Sensitivity (10σ,1hr) (μJy)		Confusion limit (1σ, 30 beams; μJy)		Time to confusion limit (10σ; hrs)	
	850μm	450μm	850μm	450μm	850μm	450μm
100	50	100	90	40	0.3	6
50	200	400	400	400	0.3	1
30	560	1100	1000	950	0.5	0.8
JCMT (SCUBA-2)	3300	17000	2000	4000	3	20

4.1. Choice of site

The sensitivity of SCOWL, particularly at short wavelengths, is very dependent on the atmospheric precipitable water vapour content; this is illustrated below, where the sensitivity is given for a typical observing elevation of 60 degrees. For pwv greater than ~1mm, SCOWL will effectively not be usable at the two short submillimetre bands, although it would still be competitive at 850μm when the pwv is as high as 2mm. Clearly the telescope needs to be on a high, dry site.

pwv (mm)	Zenith optical depth (at 225GHz)	Sensitivity (10σ, 1hr)		
		850μm	450μm	350μm
0.5	0.03	52	110	180
1	0.06	60	230	420
2	0.1	82	1000	2000
4	0.19	150	20000	50000

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