A large single-aperture telescope for submillimeter astronomy

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ABSTRACT

We describe the scientific case and design challenges for an innovative large submillimetre telescope (LST). LST is proposed to have a diameter of at least 30m, operate in the wavelength range from 0.2 – 1mm and will have a wide field-of-view. The submillimetre region allows us to probe objects during formation - i.e. the earliest evolutionary stages of galaxies, stars and planets. Being so close to the peak of the cosmic far-IR/submm background and the emission from proto-stellar cores, the 200μm atmospheric window gives access to unique science. The key advantage of LST over other facilities will be in terms of addressing astronomical questions requiring large fields and good angular resolution: such as surveys of entire giant molecular clouds and fields of dusty galaxies at early epochs. For example, such a telescope would resolve all protoplanetary disks out to 100pc, revolutionising our knowledge of star and planet formation, and detect tens of millions of dusty high-redshift galaxies yielding information on formation and evolution of the early universe. Equipped with a state-of-the-art large format bolometer camera, LST would offer a survey (mapping) speed up to 5,000 times that of ALMA, arcsecond resolution at the shortest wavelengths, point-source sensitivities at least 25 times better than any planned submm facility, and confusion limits 10 times lower than any existing single-aperture telescope. The wide-field-of-view and superb image fidelity available from a single-dish will be perfect for large-scale surveys of the submillimetre sky − an ideal complement to new generation interferometers such as ALMA.

Keywords: Submillimetre astronomy: Large single-aperture telescope, large-format imaging arrays

1. INTRODUCTION

In recent years the submillimetre waveband (0.2 – 1mm) has become extremely important for studying the very cold material associated with the earliest evolutionary stages of galaxies, stars and planets. For example, the blackbody emission of a 10K source (or a 40K source at a redshift of ~3) will peak at around 300μm. Hence to understand the *origins* of the most fundamental of astronomical structures, the submillimetre is the waveband of choice.

Submillimetre observations trace molecular (H_2) gas clouds in our own or other galaxies, using either spectral lines from trace molecules or the continuum thermal emission from dust grains. In addition, the continuum emission from nearly all objects is *optically thin* which means that observations probe right at the heart of the most crucial processes. For example, instead of looking at emission from the surface of a star or the light scattering off a disk, as in the optical regime, it is possible to look directly at material collapsing onto a central protostar. Consequently, masses and geometries can be determined in a much less model-dependent way than in the optical/IR. Furthermore, some of the coldest phenomena are *only* seen in the submillimetre: e.g. large-scale outflows from young stars, which extend far beyond the optical stellar jets and play an important role in the evolution of the surrounding cloud.

On much larger scales, the *vast majority* of UV/optical light emitted from massive stars within young galaxies is trapped within enshrouding dust clouds and re-emitted at longer wavelengths in the submillimetre. Hence only by observing at the longer wavelengths can the total energy budgets be measured. Measuring the quantity of dust in young galaxies gives a measure of the numbers of stars formed, and thus it is possible to determine whether stars have been steadily produced or formed mainly in the early Universe[1]. The enormous untapped potential of submillimetre astronomy is most clearly illustrated by considering the three main components that dominate the electromagnetic energy content of the universe (Figure 1). The dominant component is the *microwave* background produced by the primordial universe at recombination ($z \sim 1500$). The second most important is *the far-IR/submillimetre* background, now known to be produced by galaxies in the young universe at $z > 2$. The third is the *infrared/optical* background dominated by evolved stars/galaxies and AGN. It is a remarkable fact that the first and third of these components have now been mapped in detail over the entire sky, while so far less than 1 sq-degree of sky has been imaged in the submillimetre to any reasonable depth. *The submillimetre waveband remains largely unexplored territory.*

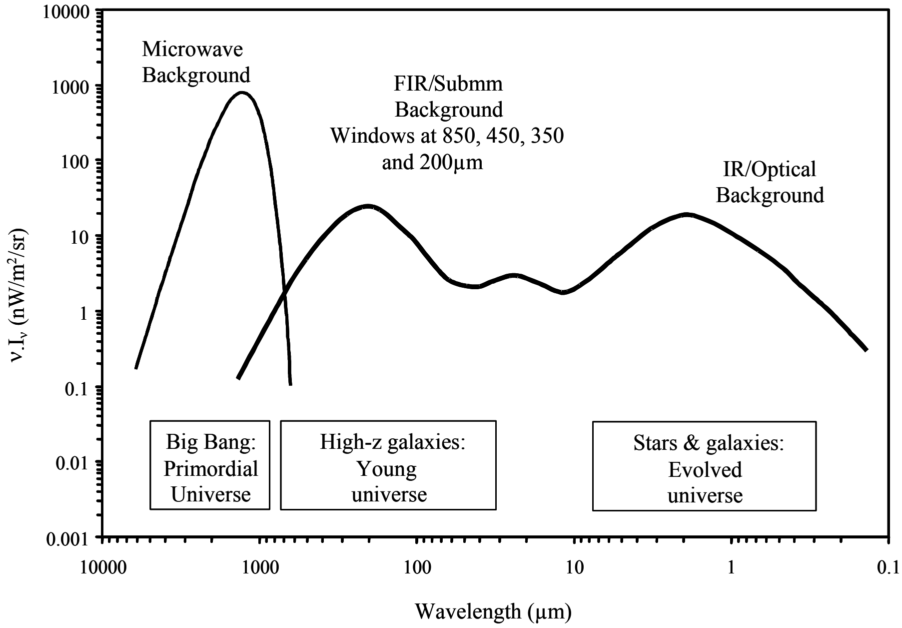

Figure 1: The spectrum of the cosmic background radiation from the optical to the microwave (adapted from Busswell & Shanks[2]).

2. SCIENTIFIC POTENTIAL OF A LARGE, SINGLE-APERTURE DISH

Undertaking observations in the submillimetre from ground-based observatories has always been a challenge since atmospheric transparency is often poor and the high background power and sky emission variability limit the observing sensitivity. Nevertheless, single-dish telescopes (of 10-15m class) are now routinely operating with high efficiency and have led to enormous advances in our understanding of the formation of galaxies, stars and planets. The impact of the SCUBA camera[3] operating on the 15-m James Clerk Maxwell Telescope (JCMT) has been immense. For example, in cosmology SCUBA has shown that the far-IR/submm background is composed of high-z ultraluminous dusty galaxies, allowing us to study galaxy formation and evolution in the early Universe[4]. SCUBA has also given us the first images of dusty belts of comets around nearby stars[5] – a vital window on planet formation.

Despite making pioneering breakthroughs in this previously unexplored wavelength regime, JCMT/SCUBA has really only given us a glimpse of what is still to come. The angular resolution, sensitivity and field-of-view available from current telescopes (and instrumentation) are severely restricted. The angular resolution from current telescopes, which at best is 8–15 arcsecs between 450 and 850µm, makes source confusion a major issue at only moderate depths. In terms of sensitivity it still takes many tens of hours to reach the extragalactic confusion limit at 850µm over the ~4 sq-arcmin field-of-view of SCUBA. Finally, current imaging arrays have only modest number of pixels (typically 100 to a few hundred). Hence surveying large areas of sky, or imaging to any great depth, is still painfully slow. Next generation imaging cameras are under development for both ground-based and space-borne observatories. SCUBA-2, a large-format imaging array[6] consisting of ~10,000 pixels in two focal planes will provide the JCMT with an unprecedented survey capability. However, the angular resolution and confusion limits will remain restricted by the 15-m aperture.

The first submillimetre interferometers (e.g. SMA) are now starting to come on-line and these will provide increase in resolving power for studying astrophysics on the smallest size-scales. Although interferometer fields can be mosaiced together to form large survey areas, single dish telescopes, equipped with imaging arrays, will remain by far the most efficient way to conduct large-area surveys. Single dish telescopes will provide a wide-field capability that is essential to exploit fully the capabilities of interferometers, such as ALMA. To achieve such a scientific complementarity would require a degree of fast-tracking the production of LST. Furthermore, there are many phenomena visible in the submillimetre which are very large (covering up to tens of degrees) but which contain significant sub-structure. Examples of these include galactic molecular clouds which have star-forming cores typically of a few arcseconds to arcminutes, and primordial galaxies which cluster over a degree but have galaxy interactions on arcsecond scales. A large single-dish is the best way to preserve flux over all these scales. Hence there is a significant void between the capabilities of existing facilities and the new interferometers with so much potential astrophysics that could be undertaken by imaging large fields with moderate resolution.

A 30m LST would provide spectacular gains in both sensitivity and mapping speed over any existing or planned facility. It would also allow an order of magnitude increase in angular resolution over facilities such as Herschel, and, from a good site, have the potential to observe at the shorter wavelengths with high efficiency. For example, a pixel sensitivity of ~10mJy/√Hz would be achievable at 450μm from a good submillimetre site (this compares with ~400mJy/√Hz currently achievable with JCMT/SCUBA). In summary, LST would deliver the following:

- A point source sensitivity surpassing that of ALMA and being *at least* 10 times better than any other current or planned facility in the submillimetre (including SCUBA-2 on JCMT). The point-source detection limits for LST and a selection of other current and planned facilities are shown in Figure 2.

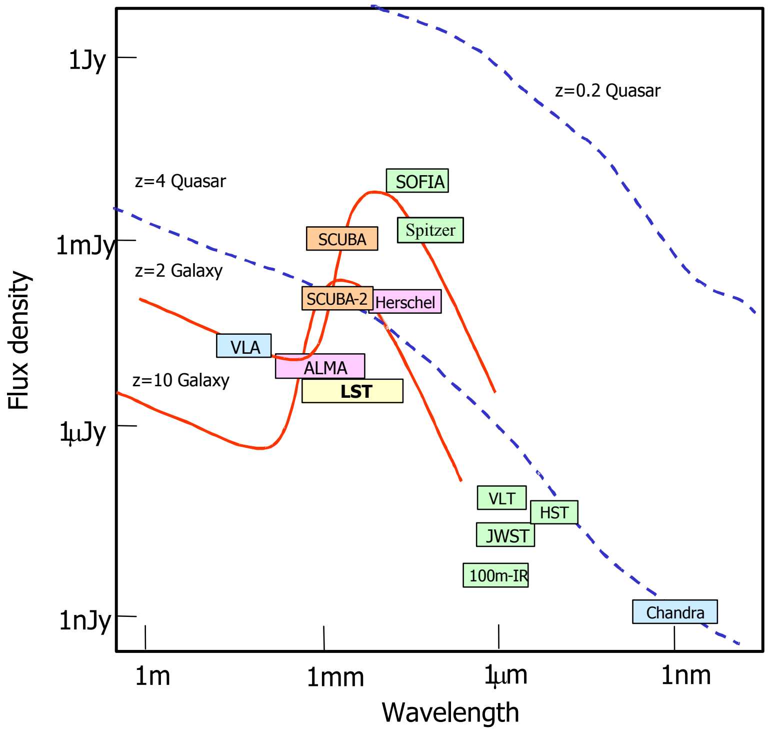

Figure 2: Point source detection limits (1σ, 1hr) for current and planned facilities. LST will detect point sources hundreds of times faster than SCUBA on JCMT. The solid and dashed curves represent "template" spectra of typical quasars and high-z galaxies. The boxes show the approximate detection limits for each telescope/instrument.

- Allow large-area surveys by offering mapping speeds *up to 5000 times faster* than can be achieved with SCUBA-2 on the 15m JCMT, or with ALMA operating in compact configuration.

- An improvement of a factor of 10 in angular resolution over currently planned satellite missions (e.g. Herschel), and a factor of at least 2 over current ground-based single dishes.

- Imaging well below the confusion limits of current single-dish telescopes. Since confusion limits will be 10 times lower for LST (operating at 200μm) than JCMT this allows images 10 times deeper to be undertaken with LST before galaxies blend together in the image.

The legacy of LST will be undoubtedly to carry out very large-scale surveys to unprecedented depth. For example, detecting proto-galaxies down to a 3σ limit ~2mJy at 850μm (the current confusion limit on the JCMT), over the entire accessible sky, would be achievable in about a year (instead of *many tens of years* even with SCUBA-2 on JCMT).

3. EXPLORING THE VERY SHORT SUBMILLIMETRE (OR FAR-INFRARED)

Although both IRAS and COBE mapped the far-IR/submm sky their crude resolution meant that they could barely pick out individual protostars from their parent molecular cloud, let alone resolve binaries or clusters. ISO was so limited by confusion at 170μm that it detected barely 10% of the far-IR cosmic background. The planned Herschel space mission has only modest resolving power (e.g. ~20 arcsecs at 250μm) so the vast majority of these fundamental objects will remain unresolved and/or below the confusion limit. Higher resolution is critical, both to resolve the emission from proto-stars and proto-planetary disks and to investigate galaxies that are representative of the cosmic background.

The 350μm window is the shortest that has so far been used for ground-based studies in the submillimetre. However, recent site monitoring[7] and analysis[8] has revealed the exciting potential of exploiting a window at 200μm from the *ground*, particularly from sites such as the Atacama Desert (Chile) and the South Pole. From such dry locations, this window is usable for up to 40% of the year and for the first time, this would allow far-IR ground-based follow-up at arcsecond resolution at the peak wavelength of the emission from dusty pre-stellar cores and of the high-z cosmic submillimetre background. With data points longwards of 450μm, it is impossible to distinguish material of different temperatures as the dust spectrum measured is that of the Rayleigh-Jeans tail and has constant slope (see Figure 3). In contrast the 200μm points are at the turnover of the emission curve and the wavelength of turnover determines the temperature. With this vital data point, it is possible to decide, for example, whether a dust core is pre-stellar or contains a warm protostar that has commenced nuclear fusion. Also, by measuring the far-IR/submm colours *direct* constraints on the redshifts of distant galaxies could be obtained (without any optical identification being required).

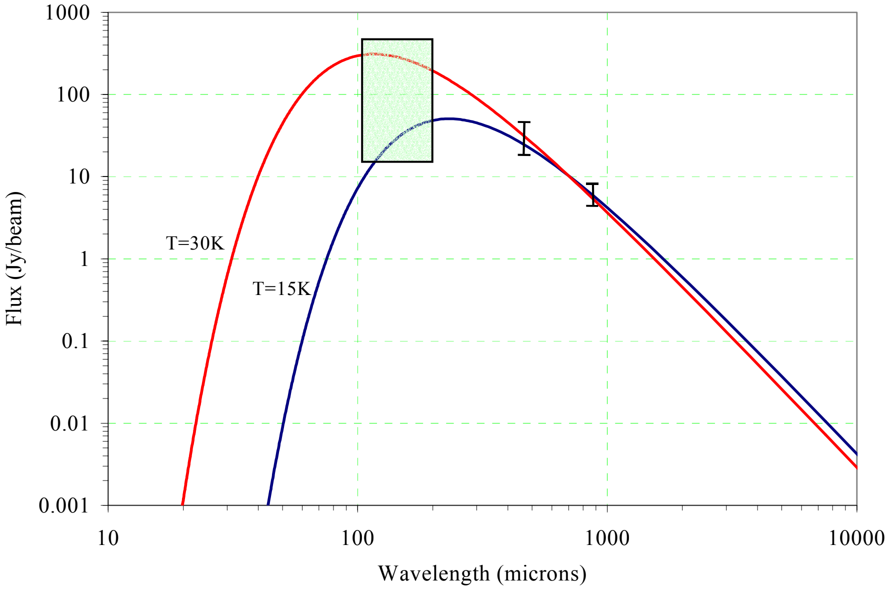

Figure 3: Illustrating the importance of the 100-200μm region for cold, un-evolved cores. Two possible greybody fits to the submillimetre spectral energy distribution (450/850μm) of a typical pre-stellar core. The 100-200μm data (region shown by the rectangle) are crucial for unambiguously determining the dust temperature.

4. TELESCOPE REQUIREMENTS AND DESIGN CHALLENGES

There are a number of challenges associated with designing a 30-m wide-field telescope. Many of these are common to the work being undertaken for the design of extremely large optical and infrared telescopes[9] and it is anticipated that the design of LST will benefit from the work currently underway in large telescope design. The submillimetre design relaxes all tolerances because of the longer wavelength and so should result in a telescope that is less complex and far less costly than an optical/IR counterpart. The rapid implementation of an LST for scientific reasons already mentioned could even help to prove some ELT technology concepts. We briefly discuss some of the design issues associated with such a telescope. In summary, the scientific drivers for LST dictate a telescope with the top-level requirements outlined in table 1.

Parameter	Requirement	Notes
Aperture	At least 30m	<2 arcsecs resolution at 200μm ~10mJy/√Hz sensitivity at 450μm
Wavelength range	0.2 – 1mm	
Field-of-view	At least 5 × 5 arcmins	Goal of 10 × 10 arcmins

Table 1: Summary of the top-level requirements for 30m submillimetre telescope.

4.1 Opto-mechanical design

The optical design needs to ensure a very wide field-of-view, a fast (low f-ratio) primary to keep the structure as compact as possible, and to provide a convenient location for the instrument bay (the re-imaged field should also have a low f-number to keep the array size manageable). Although a prime focus design would be the simplest (and cheapest) option this would not provide a convenient location for the (large) instruments. A possible optical design for the telescope is shown in Figure 4. This incorporates both spherical primary and secondary mirrors, with the induced spherical and field aberrations being removed by subsequent aspherical mirrors in the optical path. The optical design allows for a convenient and accessible location for an instrument bay (at a Nasmyth platform). Although an off-axis design (i.e. an unblocked aperture) is preferable in terms of beam obscuration, scattering and purity, it is clear that such a structure would be very expensive to build. This spherical design means that all the panels can be made the same size, thus minimising fabrication complexity and cost. The main disadvantages are that the design requires a large secondary if the structure is to be made compact. The secondary can however be made smaller at the expense of a larger structure and so an obvious trade-off will have to made.

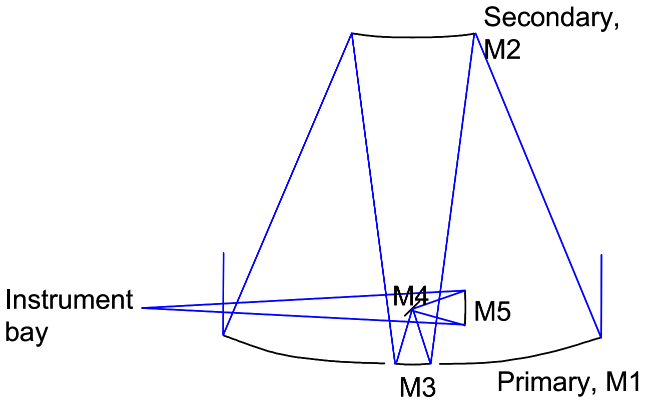

Figure 4: Possible optical design for a 30-m wide-field submillimetre telescope using spherical primary and secondary mirrors. Such a design will allow a convenient location to house an instrument bay. Should it prove necessary to adopt a sky-cancellation scheme (chopping) it is envisaged that this could be achieved using M3.

The surface accuracy required is dictated by the requirement to operate at the shortest wavelength (i.e. 200μm). The overall large-scale surface accuracy of the primary must be better than λ/20 i.e. 10μm rms. This dictates that individual panels must be better than about 5 µm rms. Panels could be made from aluminium supported by a carbon fibre backing structure, which has a low coefficient of thermal expansion as well as providing a strong, low-weight structure. A 1m diameter thin aluminium mirror has already been successfully manufactured with a surface error of < 2µm as part of the SCUBA-2 project.

4.2 Environmental impacts on design

There are also a number of environmental issues that will have an impact on the telescope design. Primary amongst these are:

- Diurnal temperature variations causing thermal distortions of the telescope optics
- Wind buffeting causing pointing and tracking drifts
- Refraction noise (or submm "seeing") causing image shift and smearing

It is anticipated that the telescope will be used for up to 20 hours a day and so must be capable of maintaining diffraction-limited imaging during the expected diurnal temperature changes. It is well known that the shape of the 15-m JCMT dish changes with temperature and this has the detrimental effect of moving source structure from the telescope main beam into the sidelobes. Active surface correction can in principle be achieved by the use of fast-reacting actuators which move individual panels as quickly as needed to correct for thermal (and gravitational) induced deformations. It should be possible to employ a system of temperature sensors over the main structural elements of LST to measure the thermal expansion of the main structure elements. Figure 5 shows how this has been implemented for the JCMT active surface control system. The temperature sensor output is then fed into a finite element model, which in turn applies the relevant corrections to the actuators on the primary mirror panels. This will allow the telescope to correct for thermal distortions and to "freeze" the surface into its optimum shape.

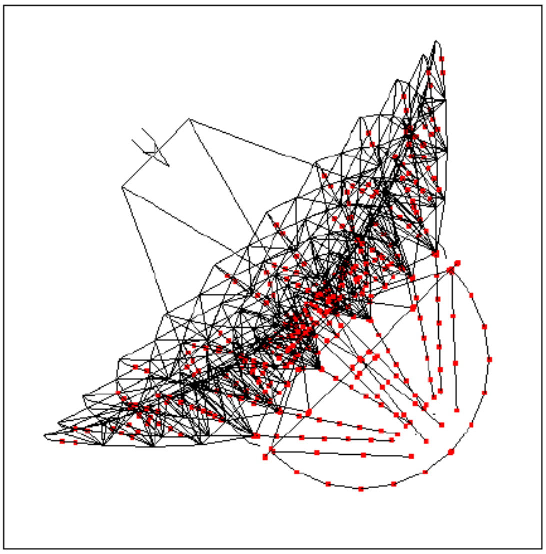

Figure 5: Side view of the JCMT showing the position of 200 temperature sensors as part of the active surface control system (figure courtesy of JCMT).

With a primary beam of only ~2 arcseconds at 200µm, accurate pointing and tracking is essential. It is anticipated that the telescope will need to point locally to at least an accuracy of 0.5 arcsecond. Whilst this is a major technical challenge in its own right, wind shake is a major concern and may dictate the need for an enclosure – perhaps incorporating a radome. Alternatively, for an open-air structure, the environmental impact on pointing stability could be compensated for by using an active real-time correction scheme. The 50-m Large Millimeter Telescope (LMT)[10] in Mexico plans to achieve this by incorporating inclinometers (mounted near the telescope elevation axis), and temperature sensors on the structure. Together with a finite element model and look-up tables these measurements give information on the structural deformations and can be used to predict and correct pointing behavior. Another possibility is the use of metrology systems to measure structural deformations directly, such as the shape of the primary and the location of the secondary with respect to the optimum configuration.

As the atmosphere drifts through the beam of the telescope fluctuations in the atmospheric refractive index causes variations in the path length from source to telescope. This is often referred to as submillimetre "seeing"[11] and can cause short-term pointing shifts which ultimately degrade the signal-to-noise of an observation, as well as image smearing. Measurements carried out on existing single dish telescopes, such as the JCMT, suggest that tilts in the wavefront across the primary aperture result in 1-2 arcsecond rms pointing errors. This is a more serious problem for large aperture telescopes which will have smaller beam sizes. The LMT plans to construct wavefront sensors to measure the tilt of the wave across the aperture. The principle is based on using 4 water vapour radiometers (similar to that used at the JCMT and centered on the 183GHz water line) to measure the atmospheric path above different portions of the LMT aperture. In principle, by measuring the column of water vapour as function of position across the dish the tilt of wavefront can be deduced and a real-time correction applied to the surface control system.

4.3 Site considerations

The Earth's atmosphere is largely opaque at submillimetre wavelengths and it is only by observing from high, dry sites that observations can be undertaken from the ground. For LST to operate at the shortest submillimetre wavelengths an exceptional site is required. The three best studied sites for submillimetre astronomy, which have been subsequently chosen as sites for large telescopes, are Mauna Kea in Hawaii (4100m), Cerro Chajnantor in Chile (5000m) and the Amundsen-Scott station at the South Pole (2800m). Peterson et al.[7] carried out a comparison of all three sites by using 860GHz tipping photometers to measure the sky brightness and hence infer atmospheric opacity and stability. They concluded that the median zenith opacity at the South Pole is 1.20, less than Chajnantor (1.39) and Mauna Kea (1.88). The study also concluded that the opacity was substantially more stable at the South Pole than Chajnantor (which in turn was more stable than MK). Hence, in principle, the South Pole is the best site for a LST, although poor sky coverage as well as the logistics of operation are major detrimental factors. Radiosonde data[8] suggest that the precipitable water vapour (PWV) level at 5700m (equivalent to the summit of Cerro Chascon in the vicinity of Chajnantor) is 2× lower than at 5000m. This would give a median PWV of 0.5mm and would imply 40% zenith transmission in the window at 200μm. The main disadvantage is that at 5700m the mean wind-speed is expected to double to around 13m/s; again, the South Pole is likely to win in the low wind-speed stakes.

5. INSTRUMENTATION

To exploit well the capabilities of LST requires state-of-the-art instrumentation. Large format imaging arrays, incorporating many thousands of pixels would be ideally complemented by spectroscopic and polarimetric capabilities. Table 2 lists a set of possible instrumentation for LST. The discussion below is confined to the status and prospects for imaging arrays, although substantial developments are also underway in spectrometer[12] and high-frequency mixer design for heterodyne focal plane arrays[13].

Capability	Field-of-view	Spectral Resolution	No. of pixels	Technology
Wide-field imaging	100-sq arcmin	~10	≥10k (see table 3)	Superconducting TES bolometer arrays
Low-medium resolution spectroscopy	20-sq arcmin	100–5000	≥2k	Grating spectrometer or FT spectrometer
High resolution spectroscopy	10-sq arcmin	of order 300,000 (1 km/s)	≥100	Superconducting mixers
Polarimetry	20-sq arcmin	~10	>2k	Cold rotating quartz half-waveplate

Table 2: List of possible instrumentation for a 30m large submillimetre telescope.

Recent advances in detector technology have demonstrated that large-format arrays of many thousands of pixels are now possible to realise wide-field submillimetre imagers. Fully-sampling an image plane and using ultra-stable DC-coupled electronics and multiplexed readouts should enable the next generation submillimetre continuum camera to produce superb high fidelity images without the necessity to sky chop. The wide bandwidths available with continuum instruments, utilising the entire atmospheric window, allows for superb sensitivity. SCUBA-2 is a new generation camera under development for the JCMT. It will fill the re-imaged focal plane of the telescope with state-of-the-art transition edge sensors (TES), with signals being read out using multiplexed SQUID amplifiers. SCUBA-2 will have two focal planes each having ~5,000 pixels over a 50 sq-arcmin field-of-view and hence will have an approximate two order of magnitude leap in the number of pixels over existing instruments. The camera will operate at 450 and 850µm simultaneously, with the output from each pixel being DC-coupled to the read-out electronics. Once in service in 2006 SCUBA-2 will map large areas of sky up to 1000 times faster than the current SCUBA array.

Table 3 summarises the pixel count for SCUBA-2 and extrapolates to what would be required to fill the focal plane of the 30m LST. To fully-populate even a 5 × 5 arcmin field would require *at least* another order-of-magnitude leap in the total number of pixels over that for SCUBA-2.

Field-of-view	**Pixel spacing**	**200µm**	**450µm**	**850µm**	**Total number of pixels to build**
~50-sq arcmins (SCUBA-2)	Fλ	–	64 × 64 (5120)		~10k
	0.5Fλ			64 × 64 (5120)	
5 × 5 arcmin (LST)	0.5Fλ	415 × 415 (178k)	185 × 185 (35k)	98 × 98 (9.5k)	~200k
10 × 10 arcmin (LST)	0.5Fλ	830 × 830 (700k)	370 × 370 (138k)	196 × 196 (38k)	~1000k

Table 3: Pixel counts required for a large-format imaging array.

In terms of the current SCUBA-2 array design there are 4 main issues that would have to be overcome to realise larger format arrays: (1) processing of silicon wafers (2) device density on the multiplexer wafer (3) power dissipation in focal plane (4) the large volume of read-out wires. The SCUBA-2 focal planes consist of 4 sub-arrays each with 1280 pixels butted together to give the full field-of-view. The sub-arrays are currently processed on 3-inch wafers due to the fabrication limitation within the project. It is fair to say that 6-inch or even 8-inch wafers could be fabricated without too much difficulty, realising at least an increase of a factor of 4 in the number of pixels per sub-array.

The SCUBA-2 multiplexer[14] has a complex design incorporating gradiometer winding and ground-plane shielding to keep crosstalk within acceptable parameters. Meeting the crosstalk requirement has necessitated the use of SQUIDs in a balanced pair (one is unbiased and acts to cancel crosstalk in unaddressed pixels). This works very well but has led to an increase in the area required under each pixel for the multiplexer circuitry. The SCUBA-2 project made the decision to adopt a larger pixel size at 450µm rather than to undertake a risky and potentially lengthy MUX re-design. However, solutions to this problem may be forthcoming with more development work.

For SCUBA-2 heat leaks down the read-out wires and array support trusses as well as SQUID power dissipation are the main contributors to heat loads in the focal plane[15]. It is necessary to have sufficient cooling capacity in the low-temperature refrigerator stage to contend with these heat loads and maintain an optimum detector temperature. The 20µW power load on the SCUBA-2 dilution refrigerator mK system is containable within the required detector performance. However, 100k arrays will likely increase this load by at least a factor of 5 so the thermal performance will become a major issue. One way to control this is to reduce the number of signal wires coming out of the cryostat. Even with full multiplexing SCUBA-2 needs of order 3500 wires. It may be possible to design a cold CMOS MUX to reduce wire count to a more acceptable level. The physical layout and heat-sinking of so many wires is also a reason for reducing the wire count as much as possible.

One final issue is how to assemble the sub-arrays together to form a focal plane. Figure 6 shows how the SCUBA-2 focal planes are constructed from 4 quadrants, with all "sub-array modules" being completely independent from each other. The signals are fed out on two-sides onto a fan-out ("bat-wing") PCB which takes up area around the sub-arrays. Sub-arrays of order 5k pixels could certainly be butted together in a similar way, but focal planes of 20k+ will need a new arrangement for reading out the detector signals. Alternatively, the sub-arrays could be offset in the focal plane to allow space for a modified readout to be incorporated, at the expense of making the focal plane larger.

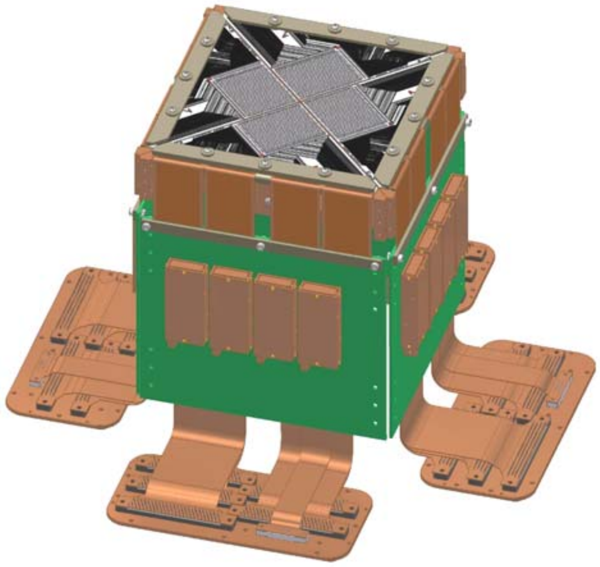

Figure 6: The layout of a SCUBA-2 focal plane. Each sub-array is contained within a sub-array module which is butted together to form the final focal plane.

In summary, it is possible that 20k pixel focal planes of TES devices, with in-built multiplexers, could be achieved within the next year or two. The step for 20k to 100k+ will require a substantial development programme and may be achievable over a 5-year time-frame.

6. KEY SCIENCE THEMES

The unique advantages of a wide-field 30m aperture telescope are that *simultaneous* large-area imaging and good angular resolution are potentially available from the same instrument. This section outlines just a few areas where LST could contribute unique science.

Galaxy formation in the early Universe

The discovery by *COBE* of the submillimetre background[16] led to the suggestion that the epoch of galaxy formation was associated with dust enshrouded star formation at $3 < z < 10$. Subsequent technological advances provided by bolometer arrays such as SCUBA[3] operating on the JCMT and MAMBO[17] operating on the IRAM 30m have allowed individual objects to be resolved from this background – the result being the discovery of a new population of distant ultraluminous FIR galaxies with space density approximately 3 orders of magnitude higher than that of their local analogues[18,19]. Their high redshifts (median $z \sim 2.4$)[20], prodigious star formation rates (>1000 M_{sun}/yr) and high CO masses[21] are consistent with them evolving to become the population of luminous elliptical galaxies found in the local universe.

Although these surveys have revolutionised our view of galaxy formation they have two major drawbacks (1) that the relatively long submm/mm observing wavelengths (850–1200μm) are far removed from that at which the background light peaks (~200μm), and (2) that the poor angular resolution (11–15 arcsec) of the surveys means that they become confusion limited before 50% of the background can be resolved[22]. A prime extragalactic science driver for LST is thus to resolve the submm extragalactic background light at a wavelength close to its peak.

SCUBA and MAMBO data have been used to predict the number counts expected from surveys conducted at 200μm (Figure. 7). These predictions are based on the model of Jameson[23] and extrapolate to 200μm by assuming that the dust emission has a greybody form with temperature 37 K, emissivity index 1.5 and critical frequency 2000GHz. The confusion limit is defined to be 1 source per 30 beams which results in a confusion limited flux density of ~ 0.1 mJy at 200μm for a 30m aperture – 10 times deeper than with SCUBA or SCUBA-2. The right panel of Figure 7 shows that at this limiting flux density the entire submm background can be resolved with LST. With redshift information the evolution of the luminosity function of the entire dust-enshrouded galaxy population can be determined.

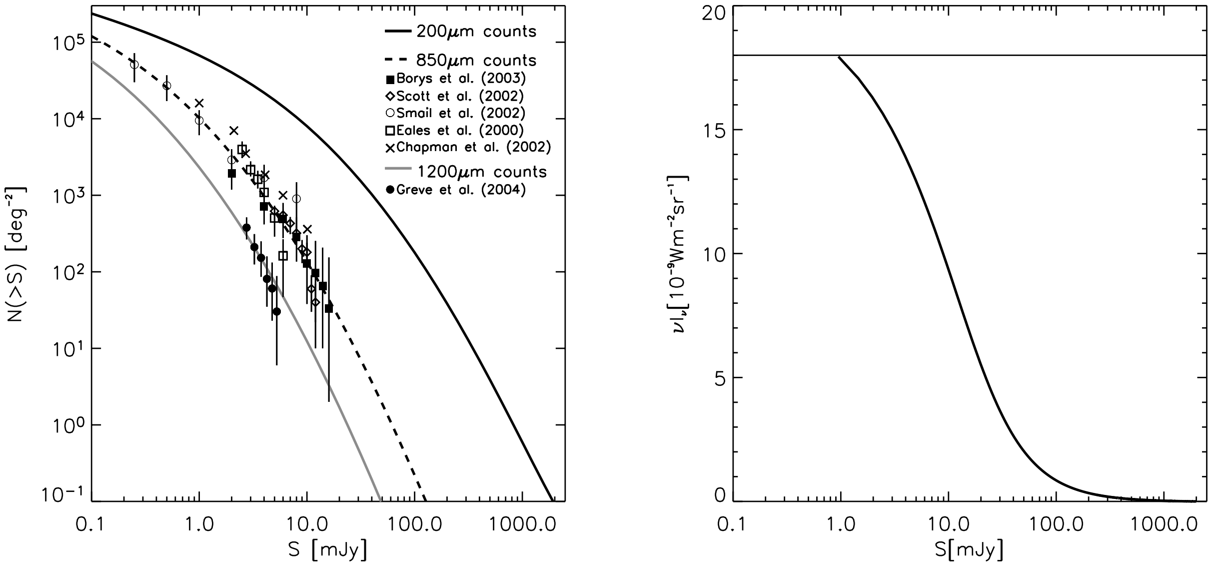

Figure 7: Left panel shows the number counts of sources detected in deep extragalactic surveys conducted with the SCUBA and MAMBO bolometer arrays. These counts have been modelled and extrapolated to 200μm. The right panel shows the result of integrating the 200μm emission from these model counts – the curve shows the cumulative energy density of the background resolved as a function of flux density and the horizontal line is the integrated background level at 200μm determined by COBE. This figure demonstrates that LST would easily resolve the background; it is important to realise that the 200μm counts are at present unmeasured and that it will be possible to make better constraints when long-wavelength Spitzer counts are available.

Large-scale clustering

The ensemble of existing extragalactic surveys with SCUBA have established the importance of dust-obscured star formation in the early Universe, and investigated the clustering of the most active galaxies on scales up to 1Mpc. Attention is now focussing on the fundamental nature of submillimetre galaxies and their role in the history of structure formation: do bright submillimetre sources really represent forming ellipticals, or merely short-lived bursts of violent activity in the progenitors of more modest galaxies? What is their relationship, if any, to high-redshift optically selected galaxies? Wide-field surveys with sensitivities well below the current confusion limit are required to address these issues. If bright submillimetre galaxies are indeed the progenitors of massive ellipticals then they should be strongly clustered, with scale lengths of around 10Mpc (roughly 30 arcmin). A survey covering 10-100 square degrees with rms sensitivity of a few hundred μJy is thus required, and this can only be done with LST. As shown in Figure 8, LST would not only give a vast increase in mapping speed over any other planned facility, but would be able to probe objects down to much lower star formation rates than current single-dish telescopes. Hence such surveys would detect many less luminous galaxies (currently selected only in the optical), allowing their clustering to be properly assessed, unbiased by obscuration, and compared with modern-day galaxy populations. Since massive ellipticals dominate the cores of rich galaxy clusters, such surveys will provide an important tracer of the growth of large-scale structure in the very early universe.

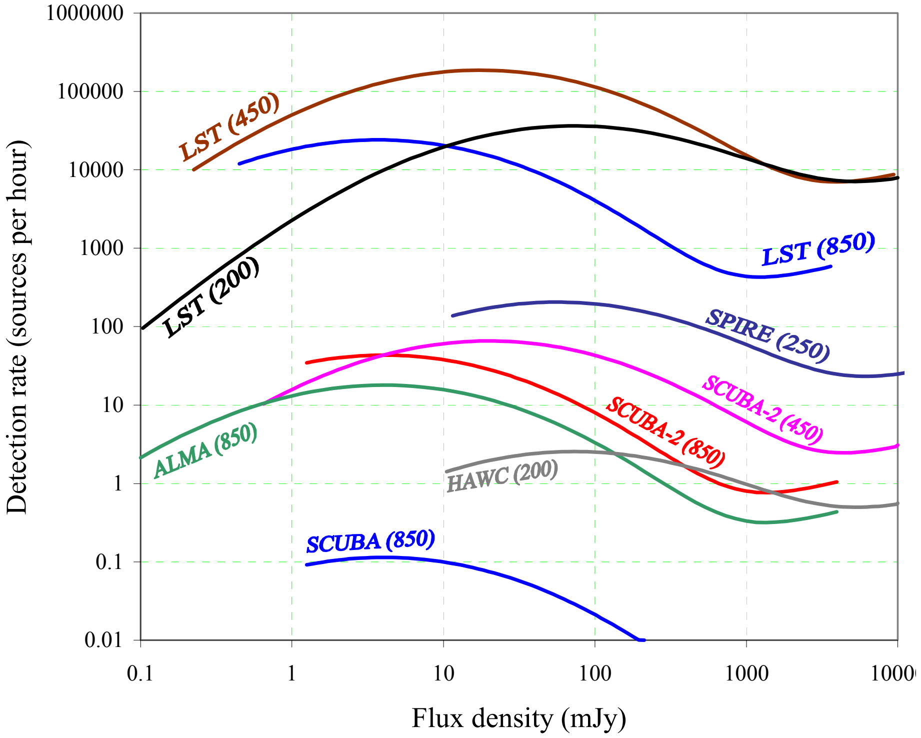

Figure 8: The detection rate as a function of 5σ depth for a range of possible galaxy surveys (adapted from Blain[24]). The curves stop at the confusion limit (left) and where the source count falls below 1/4π sr^{-1} (right).

Nearby universe

The submillimetre is a crucial regime to study star formation in nearby galaxies. Recent work suggests that surveys carried out at mid/far-IR wavelengths have missed the bulk of the cold dust emission since it resides in extended, low-surface brightness disks, often far from the galactic nucleus[25]. For example, a submillimetre study of the nearby spiral NGC 3079 revealed that 90% of the total dust mass was located within a cold galactic disk which was undetected by IRAS[26]. Hence the gas:dust ratio in nearby galaxies was likely to be consistent with the value measured in nearby GMCs and a factor of 10 lower than determined by IRAS. In terms of a Local Universe study, 2 arcseconds at z ~ 0.1 (distance of ~500Mpc) corresponds to a resolution of ~5kpc and so such a survey would resolve a population of galaxies at z ~ 0.1 – around the limit of the all-sky Schmidt surveys. Furthermore, the imaging power and resolution achievable with LST would allow the study of individual giant molecular clouds far from the galactic nucleus in more nearby galaxies. This would address fundamental issues such as whether molecular cloud-cloud shielding or high HI optical depth can result in substantial underestimates of the gas surface density, and hence seriously compromising optical studies of star formation efficiency. In addition to studying individual nearby galaxies, LST will be vital for determining the low-z benchmarks, such as the local luminosity and dust-mass functions[27], which are needed to interpret information from the deep cosmological surveys. This requires mapping of substantial portions of the sky, but poor resolution and sensitivity have hampered surveys of this kind with IRAS and subsequent missions. This is a perfect application for LST.

Star formation in our galaxy and the origin of the IMF

Simultaneous large-area imaging and high angular resolution are crucial for observing sources in our Galaxy such as star-forming clouds. For example, tracing the evolutionary spatial sequence from cold gas cores through accreting protostars to emerging T Tauri stars might require imaging a molecular cloud a degree across – but obtaining an accurate census of all objects means we also need to resolve submillimetre proto-binary systems down to arcsecond scales. Moreover, binary fractions are established very early in the evolutionary cycle - at the protostellar stage[28]. A key point is that evolving systems are *embedded* in a large background (typically only a few percent of a cloud's mass ends up in young stars), and this background dictates the pre-stellar evolution. To obtain a high-fidelity image (with the correct fluxes on all size scales) requires direct imaging at high resolution – neither interferometers nor cameras on small telescopes can provide this. *LST would offer this crucial ability for the first time.*

Sequential star formation. The large-scale triggers of star formation may be shock waves from the expansion of HII regions or supernova remnants, compressing cloud fragments that then collapse to dense cores and subsequently stars[29]. This is essentially a feedback loop in which energy injected by the first stars sets the conditions under which the next generation forms. The scale of this energy injection is currently subject to debate; for example, small stellar outflows might be a dominant local trigger. Direct submillimetre imaging and spectroscopy with good angular resolution will reveal the details of the sequential process: revealing shock fronts; measuring the numbers and densities of cores as a function of position in the cloud; mapping outflows and measuring the turbulence they add. This level of structural details requires LST, and will produce a complete census of cloud cores in various stages of the sequential process. Only LST can, for example, measure the density enhancements of faint cores above the extended background and map the steepening of the radial profiles as cores become centrally condensed over the first 10^5 years[30]. These processes occur over scales of a few arcseconds, so are not resolved by current single-dish telescopes.

Origin of the IMF. The Initial Mass Function (IMF) for stars has a remarkably uniform slope in varied conditions of star formation. This suggests the *same processes occur everywhere*, for example, fragmentation or accumulation of cores, competitive accretion, and ejection of low-mass members[31]. At present there exists no close-up view of these processes happening, nor do we understand what sets the upper and lower bounds of the IMF (e.g. 100 solar-mass star or a 10 Jupiter-mass brown dwarf). LST will enable the environments of cores to be imaged (and their velocities measured) finding direct evidence for fragmentation, dispersal and rejection processes. This detail can be matched to the sophisticated simulations now underway (see Figure 9). The data will measure the true IMF at its earliest stage, including accounting correctly for resolved binaries, eliminating transient cloud peaks and obtaining true core masses deconvolved from the large-scale background. The sensitivity achievable with LST will allow considerably lower mass limits to be obtained – potentially to Earth-like masses. These goals are not achievable with current single dishes as the cores are merged at moderate resolution.

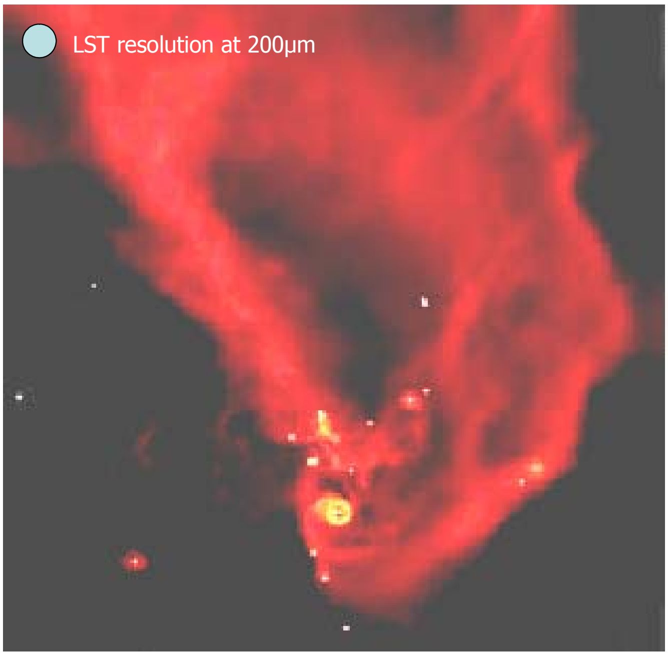

Figure 9: Part of a numerical simulation of the star formation process, showing the collapse and fragmentation of a large-scale turbulent molecular cloud to form stellar clusters, circumstellar disks and binary stars[32]. This frame shows the ejection of a brown dwarf with a resolved disk. The scale of the box is ~5000AU and the approximate resolution of LST is shown assuming a distance of 350pc (equivalent to that of the Perseus Molecular Cloud.

The formation and evolution of planetary systems

Imaging debris disks of cold dust around nearby stars can give vital clues to the planetary formation process. Not only do such images give us an effective "time series" showing how our early planetary system evolved from a circumstellar disk, but perturbations, seen as clumps and cavities in the observed image, have the potential for actually *pinpointing the locations of young planets*[30]. Although SCUBA has made pioneering breakthroughs in this area[5], it has lacked the sensitivity to study more than a handful of such objects. The remnant disks as seen from the Earth are fairly compact but can subtend up to a couple of arcminutes in diameter. Instruments such as SCUBA-2 on the JCMT can only resolve very large clumpy features (20 AU upwards). This is illustrated in Figure 10, which shows the observed debris disk surrounding Vega and a model prediction of the structure of the disk. This highlights the fact that current observational data lack sufficient resolution to fully test the uniqueness of resonance models. Arcsecond imaging with LST would improve this by close to an order of magnitude (down to ~2 AU). This would resolve, for example, gaps in the disk where dust is being accreted by migrating giant planets. Importantly, ALMA would see *only* small clumps and gaps, because a complete disk an arcminute across would be larger than the primary beam and hence be resolved out. Thus to get a true picture of the fraction of dust trapped in resonances, for example, high fidelity imaging with LST is needed.

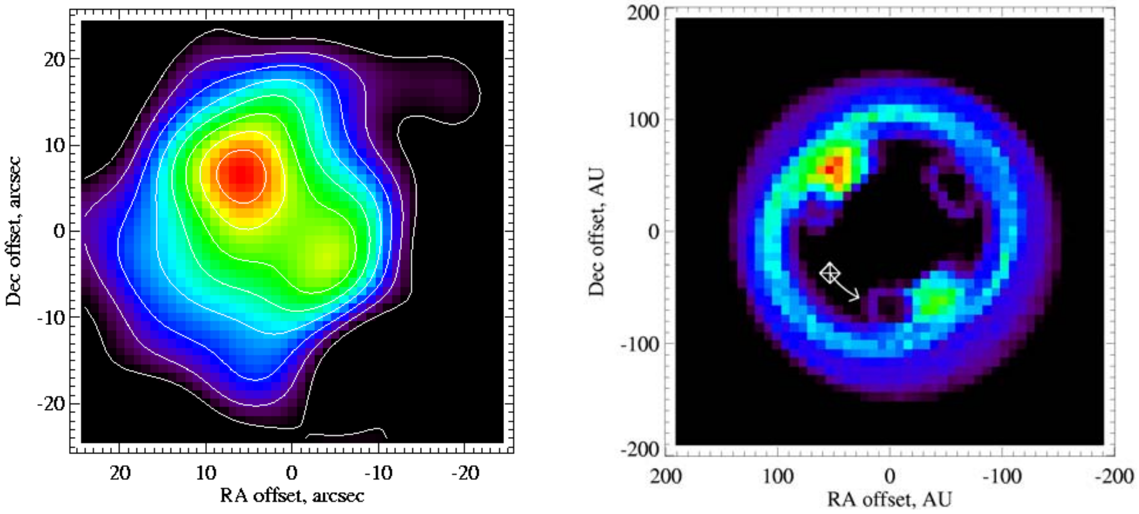

Figure 10: Left panel shows the observed debris disk around Vega[5] with 14 arcsecond resolution using JCMT/SCUBA. On the right is a model prediction[33] of the structure of the Vega disk observed with approximate 1 arcsecond resolution. The location and orbital motion of the driving planet is shown by the diamond and arrow.

7. SUMMARY

Over the next decade a significant void will exist between the capabilities of existing (or planned) single-dish telescopes and the new submillimetre interferometers. Many phenomena visible in the submillimetre extend over several degrees but also contain significant sub-structure on arcsecond scales. To obtain a true, unbiased view of the submillimetre universe, what is really needed is a dedicated large-aperture telescope equipped with state-of-the-art imaging arrays. Such a facility will offer:

- A survey speed allowing coverage of wide areas of sky rapidly and efficiently, so that generous, statistically unbiased samples can be acquired.

- Superb sensitivity to detect point sources well below current confusion limits.

- High (arcsecond) angular resolution so that galaxies and protostars are separated and *resolved* (and can be unambiguously identified at other wavelengths)

- High fidelity images with correct relative fluxes for all features, regardless of size.

LST will provide the wide-field complement that is essential to fully-exploit the capabilities of interferometers, such as ALMA. The science possibilities of LST are huge: for example, not only will we see the entire evolutionary progress from pre-stellar cores to emerging T Tauri stars, along a whole cloud complex, but also such fine details as the fragmentation of a young core into a proto-binary stellar system. Similarly, we would move away from the current situation in which we detect oddly-shaped sources in the extragalactic sky, to an era where the structure becomes resolved into a proto-cluster of galaxies, allowing us to determine star formation activity in each member galaxy.

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