The Large Southern Array

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There is great interest around the world in the possibility of a large millimetre and submillimetre wavelength array in the southern hemisphere. Europe, the US, and Japan are all working in this direction, and these projects may well merge into one global collaboration. For Europe such a facility will be of particular importance because of the strong synergy with the VLT.

1. Introduction

One of the highest-priority items in astronomy today is a large millimetre array. It will be a millimetre counterpart to the VLT and the HST, with similar scientific objectives and comparable high angular resolution and sensitivity but unhindered by dust opacity. It will be highly complementary to FIRST, SOFIA, and single-aperture ground-based telescopes. It will be sensitive to the cool dust emission and the dense forest of molecular lines unique to the millimetre wavebands, as well as the synchrotron emission extending from the radio and thermal emission from the optical/infrared. With a capability of seeing star-forming galaxies across the Universe and star-forming regions across the Galaxy, it will open new horizons in science.

Such an array should provide high angular resolution, about 0.1 arcsec at 3 mm, both for the science objectives and for compatibility with the VLT and HST. This in turn requires very high sensitivity, hence a total collecting area of about 10,000 m^2 (receivers are already reaching fundamental limits and bandwidths for spectral line observations are fixed, so larger collecting area becomes the only way to greater sensitivity). Such a collecting area implies an array with many antennas and baselines, which give the added advantage of fast, high-quality images. The site must be high, dry, large, and flat – a high plateau in the Atacama desert is ideal, and has the great advantage of being in the southern hemisphere, important for compatibility with the VLT. Thus, discussion has focused on a "Large Southern Array", or LSA.

2. Science with a Large Southern Array

The scientific case for this revolutionary telescope is overwhelming. The main science drivers are the origins of galaxies and stars: the epoch of first galaxy formation and the evolution of galaxies at later stages including the dust-obscured star-forming galaxies that the HST and VLT cannot see, and all phases of star formation hidden away in dusty molecular clouds. But the LSA will go far beyond these main science drivers – it will have a major impact on virtually all areas of astronomy, and make millimetre astronomy accessible to all astronomers. It may well have as big a user community as the VLT itself. A taste of the scientific potential of the LSA is given in the following paragraphs.

The Early Universe. Star-forming galaxies will be detectable out to $z = 20$ because of the large negative *K*-correction in the far-infrared dust emission peak. This may be the best way to find the first galaxies in the "dark ages" beyond $z = 5$, and the star-forming galaxies invisible to HST and VLT because of dust obscuration. (Sub)millimetre observations are essential to our understanding of the star-formation history of the Universe. The "ladder" of molecular transitions essentially guarantees that a redshifted line will appear in one of the observing bands. Millimetre continuum and line emission has already been detected in some of the most distant objects known, at redshifts near 5.

Gravitational Lenses. Many gravitational lenses may be found – possibly more numerous and at higher redshifts than in the optical or radio wavebands because of the very steep source count. Gravitational arcs will be mapped in molecular lines.

Quasar Absorption Lines. Quasar molecular absorption lines will be observed in the spectra of many sources. This is a new field with great potential, which was recently pioneered at the SEST. Over 30 molecular transitions have already been detected in individual absorption systems up to $z = 0.9$. In such systems one can study detailed chemistry at cosmological distances, the microwave background temperature *vs.* redshift, and gravitational lens time delays. The high sensitivity of the LSA will make a large number of distant sources accessible.

Active Galactic Nuclei. AGN can be studied "in depth", because of the low synchrotron and dust opacity and the unprecedented angular resolution of millimetre VLBI. The LSA will provide millijansky VLBI sensitivity, corresponding to brightness temperatures as low as 10^2–10^4 K. The optically-obscured molecular tori and the circumnuclear starbursts of nearby galaxies can be resolved. The presence of central black holes can be studied kinematically in a large number of galaxies.

Normal Galaxies. The LSA will make observations of normal galaxies at $z = 1$–2 with the same detail as is presently possible in nearby galaxies. The main dynamical features of nearby spirals will be resolved with enough resolution and sensitivity to constrain theoretical scenarios of galaxy evolution. The mass spectrum of molecular clouds in galaxies of different types will be determined.

Magellanic Clouds. In the Magellanic Clouds, large statistical samples of many types of objects at essentially the same distance can be studied and compared in detail with the corresponding objects in the Galaxy: molecular clouds, star-forming regions, SiO masers, circumstellar shells, supernova remnants.

The Galaxy and the Interstellar Medium. The galactic centre and its environs can be observed free of obscuration. High resolution is essential to distinguish SgrA* from confusion in this crowded region. Interstellar molecular absorption lines will be studied along a great many sight-lines towards extragalactic sources. An interferometer is essential to resolve out contaminating extended emission, and the sight-lines are guaranteed to sample random (unperturbed) clouds, as the background sources are extragalactic.

Astrochemistry. Galactic molecular clouds and astrochemistry will of course be major targets for the LSA. It will be used to study the conditions at the start of cloud collapse near star-formation regions and the interactions of newly-born stars with nearby molecular clouds. It will allow vastly improved chemical abundance analysis, limited only by intrinsic line blending. Observations of Galactic and extragalactic molecular clouds will provide comparative studies of chemistry and abundance variations.

Protostars and Young Stellar Objects. The elusive protostars may best be found by virtue of their cold dust emission at millimetre wavelengths. High angular resolution is required to distinguish objects at different evolutionary phases within the same star-forming region: the collapsing cloud cores, cool dust envelopes, hot dust cocoons, hot molecular cores, bipolar flows, ultra-compact HII regions, etc. The LSA will reveal the dynamics of the dust-obscured protostellar accretion disks, the rate of accretion and infall from the molecular clouds, and the mass distribution over the disk. Indirect evidence for planet formation may be provided by the presence of gaps cleared by large bodies condensing around the stars. The molecular outflows will be observed in unprecedented detail; masers (both molecular and atomic) might make it possible to study the innermost regions, and could reveal the velocity structure of the accretion disk.

Stellar Evolution. The LSA will detect tens of thousands of stars over the entire H-R diagram, and allow major advances in virtually all fields of stellar astronomy. Millimetre emission has already been detected from O and B stars, W-R stars, hot stars with shells, pre-main sequence stars, late-type giants and supergiants, and optically variable stars. Circumstellar shells around evolved stars, observed at millimetre wavelengths, provide a unique probe of time-dependent chemistry. The LSA will resolve thousands of such shells, and reach across the Galaxy, so that dependence on stellar type, local environment, and galactocentric distance can be studied.

Planetary Nebulae and Supernova Remnants. The LSA will provide detailed line and continuum images of planetary nebulae and supernova remnants. Radio supernovae are first seen at high frequencies, and the LSA will detect them out to large distances; VLBI can be used for absolute distance determination. SN 1987A in the Large Magellanic Cloud will be a prime target for the LSA. Evidence of a central source may require millimetre-wave observations because of possible free-free and dust absorption. The shock wave will hit the [OIII] ring in 2005 $\pm$ 3, providing an incentive for early operation of at least part of the array!

Planets. Combined observations using the LSA in conjunction with spacecraft will greatly enhance studies of the planets and their satellites. Millimetre continuum observations probe the deep atmospheres of the giant planets or the surface layers of the terrestrial planets. Millimetre heterodyne spectroscopy allows the detection of narrow spectral lines and measurement of small molecular abundances. Temporal monitoring reveals composition changes as a function of season and climate. The LSA will also detect and resolve the atmospheres of planetary satellites (*e.g.* SO_2 from volcanic activity on Io).

Asteroids and Comets. The LSA can study the size and albedo of asteroids, and probe their sub-surface temperatures. LSA continuum observations of comets will explore dust sizes not accessible to optical or radio observations. Spectroscopic observations will determine the molecular composition of the nuclear ices sublimating into the coma, and search for new molecular species. Comparisons with molecular cloud cores will provide clues to the origin of comets.

Extrasolar Planets. The LSA may play an important role in the search for extrasolar planets through accurate astrometry, possibly even direct detection. The detection of planetary atmospheres would of course be of fundamental importance.

Finally, the LSA as one element of a VLBI array will revolutionise millimetre VLBI, which is presently seriously sensitivity limited, giving images with a resolution of 50 micro-arcseconds.

3. The LSA Project

Europe has a strong involvement in millimetre astronomy: the 5 $\times$ 15 m IRAM array on Plateau de Bure, the 30-m IRAM antenna, the 20-m at Onsala, the 15-m SEST, the 15-m JCMT, the 10-m HHT, and others. Over 60 institutes around Europe use these facilities, and many institutes have developed technical expertise and leadership in this area together with European industry, so it is natural that a European collaboration should be looking to the future.

The idea of a European southern millimetre array was discussed at a meeting at ESO in May 1991, and the current concept of the very large collecting area of the LSA was proposed later that year. In May 1994 the STC reconfirmed its support for millimetre astronomy at ESO, and initiatives were taken which led to the establishment in 1995 of an LSA Project collaboration between ESO, the Institut de Radio Astronomie Millimétrique (IRAM), the Onsala Space Observatory, and the Netherlands Foundation for Research in Astronomy (NFRA). This consortium of observatories agreed to pool resources for a two-year study, which included site surveys in Chile and critical technical studies. A workshop on “Science with Large Millimetre Arrays” was held at ESO in December 1995, and the proceedings were published the following year in the ESO Astrophysics Symposia Series. A report published in April 1997 (“LSA: Large Southern Array – Combined Report”) summarised the first two years of the study, and concluded the first phase of the LSA project.

An important step was taken in June 1997. A similar project is under study in the US (the “Millimetre Array”, MMA), and an agreement was made with the US National Radio Astronomy Observatory to explore the possibility of merging the two projects into one. Until then the emphasis in Europe had been on a very large (10,000 m^2) collecting area provided by 16-m antennas operating at purely millimetre wavelengths, while in the US the concept was a smaller (2,000 m^2) array of 8-m antennas with good submillimetre performance. However, as there is also considerable interest in Europe in submillimetre observations, and in the US in a larger collecting area, a compromise seemed feasible.

Three joint working groups were set up to explore the possibility of a collaborative project: a technical working group to study the feasibility of large submillimetre-quality antennas, a science working group to review the science objectives and array concept, and a management working group to explore the possible organisational structure, both between ESO and NRAO and with Chile. It was concluded that a homogeneous array of 64 $\times$ 12 m antennas, providing submillimetre performance with a total collecting area of 7,000 m^2, could be built within the target budget of $400 m. The array would be located at the high (5000 m) Chajnantor site, an hour from the array control centre at San Pedro de Atacama. The project would be a 50–50 collaboration between ESO and NRAO on behalf of their respective communities. In Europe, ESO would draw on its own resources for project management, and involve specialised institutes for their technical expertise. The observatory would probably be run by a Chilean Foundation, incorporated in Chile and controlled by an ESO-NRAO Board.

This concept is presently being elaborated, both in Europe and the US. Eight joint working groups have been established, involving over 80 persons from the European side alone, and design work is underway. The original European consortium has been enlarged to include representatives from all ESO member states, and a Feasibility Study is being carried out. It is intended that a formal proposal be submitted to ESO Council for approval by the end of 1999.

Meanwhile, in Japan there is another millimetre array project, the "Large Millimetre and Submillimetre Array" (LMSA), and it has recently been decided that the LMSA will also be located in the Chajnantor area, less than 10 km from the LSA/MMA. As a result, the two most likely scenarios are (1) a "handshake" arrangement in which the LMSA and LSA/MMA remain independent but sometimes work together in a single large configuration, or (2) a complete merger of all three projects into a "World Array". This should be decided sometime this year. Still other countries are also interested in participating, and would likely do so under the umbrella of one or another of the major partners.

4. Conclusion

It now seems virtually certain that there will be a large millimetre and submillimetre array located in northern Chile. In view of the outstanding scientific potential of this new telescope and the strong synergy with the VLT, the participation of Europe, both scientifically and technically, is highly desirable. Whether it does participate should be known by the end of next year. The telescope will most likely be built in the period 2003–2008, and become incrementally operational over that period.

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The LSA would not be ESO's first venture into millimetre astronomy. ESO has been involved in this field for well over a decade, through its participation in the Swedish-ESO Submillimetre Telescope (SEST). The following papers summarise some of the recent scientific developments and results from the SEST.

SEST UPGRADES AND REPORTS FROM SEST OBSERVERS

SEST Upgrades

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The Swedish-ESO Submillimetre Telescope (SEST) has been in operation successfully for close to 10 years, the first scheduled observations having taken place in April 1988. It has served not only the Swedish-ESO community, but 10% of the Swedish observing time has been used by Finnish astronomers and, recently, Australia has signed an agreement with Sweden, also for 10% of Swedish observing time. The SEST receivers have been upgraded on a regular basis during the past decade, but the original control system is still in place. However, during the past couple of years an in-house project to replace this control system as well as the old computers has been in progress, while continuing normal observations. The project is being carried out by the SEST engineers with assistance from the staff at Onsala Space Observatory and will be completed during 1998. This article will describe the present instrumentation, the new control system and give a brief overview of the plans for the SEST during the coming years.

1. Current Status

The SEST instrumentation presently consists of state-of-the-art SIS receivers covering the 3, 2, 1.3, and 0.8 mm atmospheric windows, and a single-channel bolometer covering the 1.3 mm window. Receiver temperatures are typically on the order of 100–150 K (Single Side Band, SSB), except for the 0.8 mm receiver, which has a receiver temperature of about 300–400 K (SSB). Three Acousto Optical Spectrometers (AOS), two wide band (1 GHz) and one narrow band (86 MHz), each with about 2000 channels, can be used in different combinations with the 3 and 2 mm receivers or the 3 and 1.3 mm receivers simultaneously. During 1997 the three AOS were upgraded with new CCD and electronics by the group from the University of Cologne who designed and built them. This upgrade was needed to ensure ongoing maintenance support, improve the performance of the AOS and prepare them for the new control system.

The telescope, its receivers, spectrometers and other instrumentation are presently controlled by HP1000 computers via HP/IB interfaces and CAMAC controllers. The current control system is very slow due to the old computers and there are other operational limitations; e.g. because there is insufficient computer memory, only two spectrometers can be used simultaneously.

More detailed information about the SEST and its performance can be accessed through the SEST homepage, which is constantly being updated:

http://www.ls.eso.org/lasilla/Telescopes/SEST/SEST.html

2. The Control System Upgrade

The system upgrade essentially consists of replacing the HP1000 computers with a fast HP/B132L workstation and the CAMAC controllers, for telescope and subreflector control, with VME systems. The spectrometers will be controlled by a PC running Linux. The new user interface, *Pegasus,* is a graphical user interface (gui) developed at CFHT (Canadian-French-Hawaiian Telescope). It is used to control the 20-m telescope at Onsala Space Observatory in Sweden, thus a large part of the software developed there has been transferred and adapted to the SEST. The new system will be considerably faster and it will be possible, for example, to use all three spectrometers simultaneously in different combinations with the receivers.

The *Pegasus gui* is very easy to operate and allows the observer to send *all* commands by opening control windows and using the mouse to click on control buttons. An example of what such a setup may look like is given in the figure. On the top of the screen the menu bar gives access to different windows, which can be selected by the observer. Thus, by simply clicking on different buttons in the menu, the observer can, for example, open source catalogues, track a source, choose the receiver/spectrometer setup, search the *Lovas* line catalogue, tune the receivers and then start mapping routines. Thus, the new system is very user-friendly and extremely easy to use and observers will be able to quickly adapt to the gui. The data obtained will be written in FITS format and various data reduction programmes, e.g. CLASS and DRP, will be available on-line.

In November/December 1997, we used a long maintenance period to do initial testing of the new telescope con-