Science with Large Millimetre Arrays

A Summary of the ESO-IRAM-NFRA-Onsala Workshop

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The next major step in millimetre astronomy, and one of the highest-priority items in radio astronomy today, is a large millimetre array with a collecting area of up to 10,000 m^2. A project of this scale will almost certainly require international collaboration, at least within Europe, and possibly with other major partners elsewhere. In order to establish a focal point for this project within Europe, a study has been undertaken by the Institut de Radio Astronomie Millimétrique (IRAM), ESO, The Onsala Space Observatory (OSO), and The Netherlands Foundation for Research in Astronomy (NFRA). In the context of this project, a workshop attended by some 100 participants was held at ESO Garching on December 11–13, 1995 to discuss the scientific advances which such an array will make possible.

In his opening remarks, the Director General of ESO, Riccardo Giacconi, stated that ESO is committed to supporting the large millimetre array project as the possible new major prospect in European ground-based astronomy. He added that the form and extent of this support will have to be discussed in the relevant committees.

The array concept under study has been outlined in a recent document ("LSA: Large Southern Array"), which is available from IRAM or ESO. The initial concept was briefly reviewed at the workshop by D. Downes: an array of some 50 × 16 m antennas with baselines up to 10 km, operating at a site in northern Chile above 3000 m altitude to wavelengths as short as 1 mm, providing the high sensitivity of a collecting area of 10^4 m^2 and angular resolution better than 0.1″. He pointed out that this array would be a reasonable next step in terms of collecting area, at the cost of a small scientific satellite. These parameters set the scene for the following talks.

The array was placed in the context of 21st century astronomy by M. Longair*, who described it as a millimetre equivalent to the Hubble Space Telescope, one which will open up new ways to tackle many of the most important problems of astrophysics. Star-forming galaxies that would be difficult to see with HST will be detectable out to redshifts of ~ 10–20, thus providing a window into the 'dark ages' beyond z ~ 5 when much of the key activity in galaxy formation may have taken place. With its high sensitivity and angular resolution, the LSA will be particularly well suited for studying gravitational lensing of high redshift galaxies – strong lensing, weak lensing (the shear field), and cluster arcs. Millimetre astronomy is currently undergoing a revolution, with observations of the high redshift Universe and an increasing diversity of objects, and Longair concluded that the LSA will play an important part in the multi-wavelength approach to the great problems of astronomy.

The study of young galaxies in the early Universe is one of the main science drivers for the LSA, and there were presentations by S. White, G. de Zotti, P. van der Werf, M. Rowan-Robinson, and A. Blain on this subject. White pointed out that HST images of distant "protogalaxies" already show them to be complex structures suggesting that they are gas-rich and dynamically evolving; the LSA will be capable of studying them in detail, and determining their space distribution over a large redshift range for comparison with theories of large scale structure evolution. De Zotti stressed that very strong dust emission may be the dominant signature of young galaxies, in which case millimetre observations will be the principal means of finding young galaxies in the early Universe and understanding their evolution. The uniform sensitivity to such galaxies over a large redshift range may even provide an opportunity to investigate the geometry of the Universe. Rowan-Robinson placed the LSA in the context of other FIR/mm surveys for distant galaxies using IRAS, ISO, SCUBA, and FIRST. A survey with the LSA would be completely dominated by galaxies at high redshift; it would have unprecedented source density, the highest proportion of z > 2 sources, and exceptional positional accuracy and resolution. A. Blain concluded that as many as 10^4 galaxies at z > 5 may be detectable in both line and continuum with the LSA, and that gravitational lenses could be up to a thousand times more numerous in the mm waveband than in optical/radio. P. van der Werf reviewed existing mm searches for, and observations of, high-redshift galaxies, commented that our own Galaxy could be detected up to z ~ 3–5 in CO or the 158 μm [CII] line with the LSA, and discussed search strategies. At still higher redshifts, P. Encrenaz discussed the prospects of searching for primordial molecules such as LiH and LiH$^+$.

The potential of the LSA for studying high-redshift quasars and quasar absorption systems was highlighted by the presentation of new results by A. Omont and T. Wiklind. Omont showed detections of mm continuum radiation from the highest redshift quasars; observations with the Plateau de Bure interferometer indicate that the emission from the z = 4.7 quasar APM 1202-07 comes from two components, the quasar itself and another object at the same redshift 2.5″ away. The LSA will make it possible to map such emission and search for other such objects, some of which may be dust-obscured. Wiklind showed results from the exciting new field of molecular absorption-line spectroscopy of quasars. As many as 15 distinct molecular transitions have already been detected in individual absorption systems in quasar spectra out to redshifts of 0.89; the highest-redshift system was discovered purely by spectral scans in the millimetre wavebands, in a radio Einstein ring which has not yet been optically identified. Several molecular transitions have been detected in individual systems. The LSA will greatly expand this work, by virtue of its high sensitivity and discrimination of point sources against extended emission, making possible such important measurements as gravitational lens time delays, the temperature of the microwave background as a function of redshift using different molecular transitions, and isotopic ratios at cosmological distances.

The LSA will contribute to studies of the physics of active galaxy nuclei, with its high sensitivity, its discrimination of point sources, and its ability to probe deeply into galactic nuclei because of low synchrotron and dust opacity at millimetre wavelengths. T. Krichbaum described the kinds of science that will be possible if the LSA can be used as a phased array for mm VLBI. At wavelengths shorter than 3 mm, VLBI is capable of resolutions of a few tens of microarcsec, corresponding to fractions of a parsec at z = 1. Space VLBI at mm wavelengths would provide still higher resolution. Unprecedented sensitivity would also be possible: ~ 1 mJy, corresponding to brightness temperatures T_B ~ 10^2–10^4 K and T_B ~10^4–10^6 K for

* Owing to transportation difficulties, M. Longair and J. Crovisier were unable to attend the workshop, and their papers were presented by A. Blain and P. Encrenaz respectively.

Current state-of-the-art in millimetre arrays: the four 15-m antennas of the IRAM interferometer on Plateau de Bure, France. Photo: A. Rambaud, IRAM.

baselines of hundreds and thousands of kilometres respectively. A variety of new observations would become possible, ranging from the immediate environs of supermassive black holes in galactic nuclei and extragalactic mega-masers, to milliarcsec imaging of Galactic objects with relatively low brightness temperatures (particularly stars and stellar winds) – a new field of scientific research. S. Wagner discussed variability as a diagnostic of AGN, and pointed out that the high sensitivity of the LSA will allow monitoring of a large fraction of the flat-spectrum radio-loud quasars in the Universe. R. Chini discussed mm continuum observations of AGN and galaxies, showing how a combination of infrared and millimetre observations can distinguish between types, even if optically obscured. High resolution millimetre continuum maps of galaxies can provide a powerful tool for studying star formation.

Several presentations by F. Combes, C. Henkel & T. Wiklind, D. Downes, F. Viallefond, R. Genzel and L. Tacconi concerned molecular line studies of galaxies. The LSA will be able to resolve individual clouds in other galaxies and achieve the same angular resolution for galaxies at $z \sim 1$ as can be achieved now in local galaxies, which will provide direct information on galaxy evolution. The main dynamical features – spiral arms, secondary bars and rings – will be resolved with enough sensitivity to constrain theoretical scenarios. The mass spectrum of molecular clouds in nearby galaxies will be determined, as will insights into large-scale star formation processes and the H_2/CO ratio. Special studies, such as mapping of gravitational arcs in molecular lines, will be possible. The LSA will address questions such as the origin and kinematics of the molecular gas in early-type galaxies. It will make possible detailed studies of the central regions of galaxies – molecular tori and rings, and nuclear star formation. The large collecting area and high sensitivity of the LSA will be required to spatially resolve the tori in AGN (NGC 1068 could be observed with 3 pc resolution), and to kinematically detect the central engines. The Magellanic Clouds provide a laboratory for interstellar medium and stellar studies, and F. Israel summarised the wide range of objects that will be detectable with the LSA.

In our own Galaxy, many classes of objects could be studied in unprecedented detail. P. Mezger pointed out that, if SgrA* at the Galactic centre is an underfed black hole, and if such objects occur in most galaxies, then as the closest example it will be very important to study in detail. The LSA would permit unobscured study of this object and its environment. R. Lucas explained how the LSA will be particularly suitable for the study of diffuse molecular clouds in absorption against extragalactic sources; thousands of sources will be accessible to the LSA, and as they will sample random (unperturbed) clouds, they will be ideal for unbiased statistical studies. T. Wilson and M. Walmsley discussed the potential contributions of the LSA to our knowledge of molecular clouds and astrochemistry. The large interferometer would contribute most from studies of molecular clouds near star-formation regions – the conditions at the start of cloud collapse, and the interaction of newly-born stars with nearby molecular clouds. Spectral scans with high resolution and sensitivity, and molecular maps with the same high angular resolution as the continuum maps, will provide new information on the chemistry, dynamics, and evolution.

Observing and understanding the formation of stars and planets is another of the main science drivers for the LSA, and was covered in talks by M. Felli, S. Beckwith, A. Dutrey, R. Bachiller, and several poster papers. The elusive protostars may best be found by virtue of their cold dust emission at millimetre wavelengths, and a large millimetre array will be ideal. In the early collapse phase the disks will be opaque at mm wavelengths, so easy to detect in the continuum. Other clues to the presence

The Director General of ESO, Riccardo Giacconi, giving his opening remarks at the workshop.

of young stellar objects – infrared and maser emission – can be followed up at high angular resolution by the large array. The earliest phases require high angular resolution in order to locate the thermal dust emission, the high density molecular clumps, and the small-scale molecular outflows. The study of the evolution from disk to planet formation will require line and continuum observations with an angular resolution of 0.1″ and high sensitivity. One would like to study the morphology and kinematics of disks, the presence of rings, the distribution of molecules and dust. Molecular outflows are important both as an essential ingredient of star formation and for an understanding of the physics of astrophysical jets in general. K. Menten and C. Thum discussed molecular and recombination line masers from stellar envelopes. In addition to the study of the envelopes themselves, these masers can be used for a variety of purposes, ranging from distance measurement to "maser guide stars" that can assist in imaging faint emission around the stars.

The LSA will produce a quantum jump in the multi-wavelength continuum study of stars, as summarized by R. Pallavicini – thousands of stars of many types over practically the entire HR diagram will be detectable. This work will have an impact on studies of the winds of early stars, the photospheres and chromospheres of giants and supergiants, thermal emission from other evolved stars, the disks of pre-main sequence stars, the non-thermal emission from active stars, etc. By observing at mm wavelengths, one can go deeper into a stellar atmosphere, and explore a higher energy (> 1 MeV) electron population in flares. Measurement of the optically-thick free-free emission from the photospheres of normal stars will permit the determination of stellar radii for those stars with well-determined parallaxes. C. Fransson pointed out that the LSA will also be important for supernova research, as radio supernovae are first seen at high frequencies, and the LSA will be able to detect them out to 30 Mpc. VLBI studies of supernovae can be used for distance determinations. The angular resolution of the LSA will be important in the study of supernova remnants and their proper motions. In the case of SN 1987A, the fact that the LSA and HST will have similar angular resolution will be important; the prediction that the supernova shock wave will hit the [OIII] ring in the year 2005±3 may provide impetus for an early construction of the LSA!

Molecular line observations of circumstellar shells around evolved stars provide a unique probe of time-dependent chemistry, and M. Guélin indicated that the LSA will be capable of resolving these shells at distances of 6–10 kpc, the distance of the Galactic molecular ring. Planetary nebulae were described as "dust factories" by P. Cox, and LSA studies will provide important information about the process of interstellar enrichment. Many species of molecules have already been detected in 44 planetary nebulae, and the LSA will greatly advance such studies.

The study of solar-system objects would greatly benefit from combined observations using the LSA in conjunction with spacecraft. The LSA will contribute much to planetary science – our own solar system and possibly evidence about extrasolar planets. A. Marten described the progress that has been made from close encounters with planets by some two dozen spacecraft, and said that millimetre observations with the LSA would contribute to a wide variety of topics – composition, isotope studies, thermal structure, dynamics (winds), meteorology. LSA continuum observations of asteroids would complement radiometric observations at other wavelengths, contributing to the determinations of their size and albedo, as outlined by J. Crovisier*. In addition, it would provide the unique possibility to sample their subsurface temperature and study their thermal properties. LSA continuum observations of comets would explore dust sizes not accessible to optical or radio observations – the large-size particles of the dust coma. Millimetre spectroscopic observations would be important to determine the molecular composition of the nucleus ices sublimating into the coma, to study the kinematics of the cometary atmosphere and to investigate its physical conditions, as well as searching for new molecular species. The combination of high angular resolution and high sensitivity provided by the LSA would permit the study of the structure and evolution of the gas and dust jets of comets, in relation to the outgassing processes of the cometary nuclei.

J. Lequeux concluded the scientific presentations by considering the synergy between the LSA and the VLT. He pointed out that these two instruments will be highly complementary, as they will both have high sensitivity and angular resolution. Furthermore, he said that the main scientific drivers for both the LSA and the VLT are cosmology and star formation, so that the science programmes will also be complementary – these are also the domains where the synergy will be at its best. For example, in the case of high-redshift galaxies, the millimetre observations will be biased in favour of dust-rich galaxies, whereas the optical is biased against such objects.

There followed a series of presentations about the LSA Study Project, focussing on various technical aspects. R. Booth provided an overview, stressing that, with the Plateau de Bure interferometer and the 10-m HH, 15-m SEST and JCMT, 20-m Onsala, and 30-m IRAM dishes, Europe is already strongly developed in millimetre astronomy, and the LSA is a logical next step.

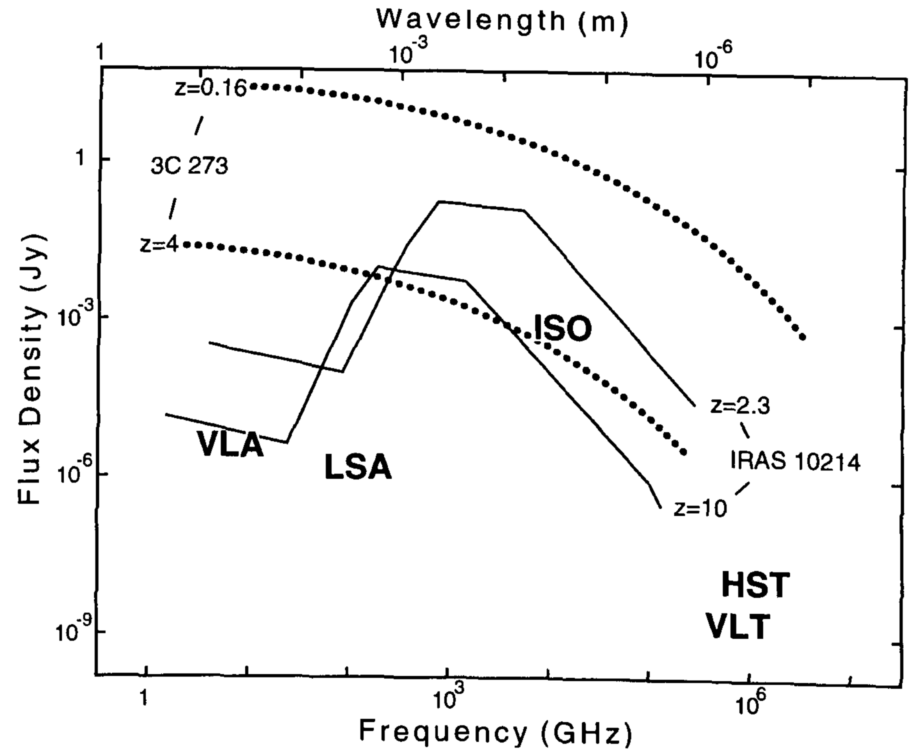
The obvious location for the LSA is the Atacama desert in Chile, both for the unparalleled atmospheric conditions and for complementarity with the VLT. L. Bååth described the search presently being undertaken for a site sufficiently large for the LSA and at an appropriate altitude and within reasonable distance of infrastructure. One site has already been identified which is worthy of more detailed study. R. Hills discussed the problem of atmospheric phase fluctuations due to water vapour, for which corrections are required in order to obtain angular resolution significantly below 1 arcsec. There are a number of possible correction techniques (also discussed in poster papers by M. Bremer and P. Hall); the most promising is based on measurements of the atmospheric emission in the beam of each antenna.

Possible array concepts and configurations were outlined by S. Guilloteau. The large collecting area of the array, together with the need for a manageable number of dishes, implies large sizes for the individual antennas. They should be moveable, to provide high sensitivity at short baselines. Some initial configuration ideas were outlined, including a hierarchical (fractal) scheme. A. Baudry also made the case for subarrays capable of quick phase calibration, and commented on the use of the extended IRAM array as a testbed. Overall technical requirements (wavelength coverage, angular and spectroscopic resolution, polarization requirements, etc.) were still to be fully defined based on scientific objectives. D. Plathner described possible novel telescope designs that would meet the required specifications at low cost.

J. Lamb commented that the provision of the large number of mixers required for the LSA would be a significant challenge. Millimetre receivers are already close to fundamental sensitivity limits, and the main advances to be made are in reliability and simplicity. Forecasting from the present he would predict SIS receivers with solid-state local oscillators, perhaps with HEMT receivers for frequencies < 150 GHz. Cryogenics would be a major issue. The correlator would also be a technical challenge, but, as A. van Ardenne showed, current developments in microelectronics are promising and the tenfold increase in correlator power is possible.

L. Woltjer concluded the workshop by again placing the LSA in context: it will be a counterpart of both the HST and the VLT, and will also serve the adjacent communities such as those of ISO, FIRST, and SOPHIA. In terms of the evolution in sensitivity and resolving power, the LSA is a logical and necessary development in millimetre astronomy, similar to that now being made in optical astronomy. He mentioned the advantages of ESO being involved in some way in this endeavour. There are many issues to be decided in the technical optimization of the LSA, and that is the purpose of the present Study Project. Funding possibilities should also be explored now, if the LSA is to be built sometime in the next decade.

The complete proceedings of this workshop will be published in the ESO Astrophysics Symposia series.



Sensitivity of the Large Southern Array for typical continuum observations, compared with that of some other large telescopes (approximate wavelength and sensitivity are indicated by the location of the telescope name in this plot). The broadband spectra of 3C273 (at z = 0.16 and redshifted to z = 4) and IRAS 10214+4724 (at z = 2.3 and redshifted to z = 10) are also shown for comparison.

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