EUROPEAN PLANS FOR A MILLIMETRE ARRAY

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Abstract. Since their very first working discussions on a next-generation millimetre telescope, European astronomers have based their ideas on a large array with a collecting area of about 10,000 square metres and a resolution of 0.1 arcsec at a wavelength of 3 mm. They have argued that the array should be built on a high, dry site in Northern Chile, strategically placed to observe the rich harvest of millimetre sources in the central parts of the Galaxy and, at the same time, benefitting from the infrastructure and astronomical base established by ESO. The collecting area of the proposed array is comparable to that of the VLA, and around an order of magnitude greater than is available today. Scientifically, such an instrument will provide a quantum leap in present day millimetre astronomy, and it will open up new directions in astrophysics. It will enable astronomers to exploit the full richness of the millimetre spectral band through the study of all types of millimetre radiation—not only the panoply of molecular lines and dust continuum from the cool gas, but the line and continuum from ionised gas and synchrotron emission from relativistic particles. The starting concept is an array with about 50×15 m dishes (or 100×10 m dishes) with 50 microns global precision, to be sited above 2000 m altitude on a site allowing baselines up to 10 km. In order to refine this concept, to review possible sites and to investigate the technology required, the Institute de Radio Astronomie Millimtrique (IRAM), the European Southern Observatory (ESO), Onsala Space Observatory (OSO) and the Netherlands Foundation for Research in Astronomy (NFRA) have recently agreed to pool their resources in a joint European study which has just begun.

1. Introduction

By way of introduction, it is interesting to take a look at the current European instrumentation for observations of CO.

The Swedish 20 m diameter, radome-enclosed telescope at Onsala was completed in the mid 70s and has recently been resurfaced and generally upgraded to give an aperture efficiency of nearly 50% at 115 GHz. In collaboration with ESO, Sweden also operates the 15 m diameter Swedish-ESO Submillimetre Telescope, SEST, on the ESO site of La Silla in the Chilean Andes. However, the major millimetre facilities in Europe were built and are operated by the French-German-Spanish institute, IRAM. They consist of a 30 m diameter antenna located on Pico Veleta in Spain and a four, soon to be 5×15 m element interferometer on Plateau de Bure in the French Alps. (The design of SEST is based on that of the IRAM interferometer telescopes). Finally, we have heard already in this meeting about the 15m James Clerk Maxwell submillimetre telescope on Mauna Kea in Hawaii, operated by the UK, in collaboration with the Netherlands and Canada and the Heinrich Hertz 10 m submillimetre antenna, a collaboration between the Max-Planck Foundation and the Steward Observatory, here in Arizona.

The abundance of results from these and other millimetre telescopes, many of which are presented in the pages of these proceedings, amply justifies the construction of a much more powerful, next generation instrument. The detection of CO and continuum emission from dust in the distant galaxy IRAS 10214+4724 (z=2.3) and in the Cloverleaf quasar, H1413+117 (z=2.5), show the potential of mm line astronomy as an investigative tool in cosmology and make large collecting area and high resolution imperatives for a new instrument in order that many more high red shift objects may be studied in detail, with sufficient spatial resolution.

The recent mapping of the star IRC+10216 in rare molecules like MgNC and NaCl illustrates the power of mm interferometry in delineating the chemistry of circumstellar envelopes. New studies of the star GG Tauri in ^{13}CO show the ability of mm interferometry to derive the kinematics of disks around pre-Main Sequence stars. Mosaic maps of galaxies like M51 show the potential of mm interferometry to map giant molecular cloud complexes in nearby galaxies.

In fact, nearly all objects studied in mm astronomy contain weak fine structure, unresolved with current mm telescopes. To resolve this structure, we need to use longer baselines, and because of this we need more sensitivity. This can only be obtained with an interferometric array with a large collecting area.

Arguments for a large millimetre array may be found in papers by Booth (1994), Ishiguro et al (1994), Downes (1994), Booth and Downes (1995) and, in a earlier context, in the MMA Proposal of NRAO (1990). On behalf of the recently formed European array study consortium, Downes, with input from other European scientists, has compiled a strong scientific case for the array discussed here. This article draws freely on that document entitled *A Next-Generation Millimetre Interferometer for Radio Astronomy.*

2. The Case for a Next-Generation Millimetre Array

2.1. ORIGINS

The millimetre spectral band is especially well matched to the study of the origins of the fundamental building bricks of the Universe - the galaxies, the stars and the planets. This is because it is the domain of radiation processes from cold matter. However, while we are tantalizingly close to important revelations in these exciting areas, we need at least an order of magnitude increase in sensitivity over today's instruments to make a serious impact.

As an example, take the case of the high z galaxies. For the first time radio astronomers can study thermal dust emission and line emission from cool neutral, molecular and atomic matter at epochs close to the formation of galaxies - their first star bursts and their first production of heavy elements. Because all these millimetre signals arise from non-exotic, low temperature emission processes, they should provide reliable estimates of densities, temperatures and masses of this material. However, in this meeting we have learned that the high-z galaxies may only be observed because their emission is amplified by gravitational lens focusing. A millimetre array with a $\times 10$ increase in sensitivity will enable us to study the main population of such galaxies without the help of foreground lensing objects.

2.2. COLLECTING AREA AND RESOLUTION

The largest European instruments today are the IRAM 30 m antenna, which has a collecting area of 700 m^2, and the IRAM interferometer, which will ultimately have 6×15 m antennas and a collecting area of about 1000 m^2. Based on the lessons of cm/dm radio astronomy, we know that major scientific improvements will come from an order of magnitude increase in sensitivity (the $70 - 100$ m telescopes v. the earlier 25 m dishes, or the VLA v. the Westerbork interferometer) and since today's millimetre receivers are within a small factor of the quantum limit, this increase will only be achieved by a significant increase in collecting area. Hence our goal of an instrument with a collecting area of $7000 - 10000$ m^2. Such a collecting area may be achieved with $40 - 60 \times 15$ m antennas.

Again, based on today's observations, we know that a resolution of about 1 arcsec is barely sufficient to resolve the high-z galaxies or the nearest protostellar discs. Thus, in resolution, an order of magnitude improvement is also desirable, which leads us to the conclusion that the proposed instrument should have a resolution of 0.1 arcsec at a wavelength of 2.6 mm, or maximum baselines of 10 km.

Observations of quasars will undoubtedly require VLBI baselines and the proposed array, phased as a single dish, will be a powerful VLBI element, improving the sensitivity of today's millimetre VLBI baselines to Chile by more than a factor of 7.

2.3. SCIENTIFIC MOTIVATION

Scientifically, a next generation instrument should provide a quantum jump in present-day millimetre astronomy, opening up new directions in astrophysics. This meeting has given us no small insight into the goals for the future but, for completion, the scientific drivers for the array are outlined below.

Cosmological studies of a large sample of distant galaxies emitting continuum radiation from dust and red-shifted ($z \geq 2$) lines of CO and other species. Even if the high z galaxies detected today are lensed, as suggested by Radford in these proceedings, the increased sensitivity of the array should be sufficient for a detailed study to be performed on a significant population, giving new insights into the cosmological evolution of galaxies and the production of the first heavy elements.

Observations of intermediate red-shift galaxies and quasars in emission and absorption lines, as well as continuum radiation (dust and synchrotron). As pointed out by Wiklind and Combes (1994), it is easier to detect small quantities of gas in absorption than emission making absorption line measurements against background continuum sources a powerful means of studying the chemistry of these intermediate red shift objects. In some cases it might be possible to detect absorption against the central continuum component of a galaxy by gas in one of its spiral arms or possibly even in the dusty torus surrounding its central black hole.

Sensitive, detailed mapping of nearer galaxies, their discs and especially their centres, including on the one hand the study of star bursts in interacting systems and on the other, the study of low metallicity systems like the Magellanic clouds.

Protostars - the resolution and dynamical studies of protostellar accretion discs and the origins of their bipolar outflows.

High resolution studies of proto-planetary discs around young stellar objects, in both line and continuum emission.

Stars - sensitive studies of the emission from all types of stars but especially the chemistry and dynamics of the cool envelopes surrounding evolved stars, giving a greater insight into the return of material by these objects into the interstellar medium.

Solar system - studies of line and continuum emission from all types of solar system objects from the giant planets and their satellites to comets and asteroids.

3. Why the Southern Hemisphere?

The case for the southern hemisphere rests on both scientific reasoning and site considerations. A large fraction of interesting millimetre sources are in the southern sky, and there are a number of good, flat, millimetre-quality sites at high altitude. In addition, through ESO we have a long history of optical data on southern objects which will be enhanced by the construction of the Very Large Telescope, VLT.

3.1. SCIENCE

There are compelling scientific reasons for building an array in the southern hemisphere. Although high red shift galaxies may be studied equally well from northern or southern sites, most other objects of interest for mm astronomy are more numerous in the south. These include the Galactic centre itself and the entire central part of the Milky Way, which contains most of the Galactic star forming regions, proto-planetary discs, circumstellar envelopes, planetary nebulae, and compact HII regions. Ironically, many of these objects are already well-known mm sources and their observation with the currently available, northern hemisphere mm interferometers is hampered by atmospheric problems and poor baseline coverage, due to the low elevation of these sources in the northern sky.

At far southerly declinations we also have the Magellanic Clouds, of special interest because of their low metallicity and clues to chemical evolution, and because of their proximity to our Galaxy. The southern sky also contains some spectacular galaxies that are prototypes for their classes. Finally, one of the nearest active galactic nuclei, Centaurus A, at Dec. -42 deg., is best observed from the southern hemisphere.

As mentioned above, there is a wealth of supplementary astronomical information to complement mm studies, as there have been major optical observatories in the southern hemisphere for a long time. Through the optical telescopes in Chile, Australia, and South Africa, and the radio telescopes in Australia, including the recent Australia Telescope, and with the Swedish-ESO Submillimetre Telescope (SEST), there are already very significant astronomical resources in the southern hemisphere to guide and to complement studies with a large millimetre interferometer.

3.2. HIGH QUALITY SITES

Some of the world's best millimetre sites lie in the Atacama Desert on the coastal side of the Andes in Northern Chile where there are many large, flat tracts of land at altitudes even as high as 5000 m. Several apparently excellent accessible sites have been identified recently by teams from Japan, Sweden and the USA, with the help of astronomers from the University of Chile, and 22 potential locations were found by Raffin & Kusunoki (1992) in a search for sub-mm interferometer sites. These sites are extremely dry, with precipitable water vapour around 1 to 1.5 mm for large fractions of the time.

Extensive water vapour measurements have been made only on Cerro Paranal (altitude 2650 m), the site for the ESO VLT. These data show that the precipitable water vapour content is below 1.5 mm for at least 30% of the April-November period, and below 3 mm for 60% of this period (Sarazin 1990; Martin 1991). Paranal is only 15 km from the ocean; more recent site testing by US and Japanese groups, again with help from the Chilean astronomers and SEST staff, is beginning to show just how excellent are the higher inland sites. The following papers by Brown and Ishiguro describing site testing at around 5000 m and 4000 m, respectively, will amply demonstrate this point.

The expanse and flatness and low water vapour content of these high altitude sites all suggest that Northern Chile is an ideal location for a large millimetre array.

4. The European Study

Four European institutes, representing much of European millimetre wave astronomy, have recently joined forces to study the proposed array. They are the Institute de Radio Astronomie Millimtrique, IRAM; the European Organisation for Astronomical Research in the Southern Hemisphere, ESO; the Onsala Space Observatory; and the Netherlands Foundation for Research in Astronomy, NFRA.

The basic concept is a large millimetre array with a collecting area of 10000 m^2, for operation over the frequency band 40 GHz to 350 GHz. It will be located on a high site, above 2500 m altitude, probably in Northern Chile, and will have baselines up to 10 km, giving a clean synthesized beam of 0.1 arcsec at a wavelength of 3 mm. The array will consist of about 50×15 m antennas, or alternatively, depending on site conditions (wind, etc.), 100×10 m antennas.

The detailed study for the array will address several important design aspects. In general, to minimize the need for interventions on a spread-out, remote desert site, a major design goal should be reliability of all components. To keep the cost to a minimum, components should be as simple as possible and capable of easy replication. In addition to site testing, particular sub-studies are foreseen as outlined below.

4.1. ANTENNAS

The antennas should be simple and robust, and well-designed to maintain their mm-quality surface (total precision 50 microns r.m.s.) in reasonably windy conditions (up to 15 ms^{-1} as a goal). Since we need to have antennas which can survive in the outdoors, without astrodomes, particular attention must be paid to their pointing accuracy and thermally stable structures must be designed. For a sufficiently large array, it might be possible to have most of the antennas on fixed stations, avoiding the need for rails and transporters.

4.2. RECEIVERS

For ease of maintenance, receivers should be modular and of robust construction. They should ideally be tunerless systems with broad instantaneous bandwidth, i.e., they should be designed to avoid complex tuning procedures. Closed-cycle cryogenic systems must be designed to be maintenance-free for long periods. The need for 4 K systems should be avoided by using HEMT technology where feasible.

4.3. INTERMEDIATE FREQUENCY SYSTEM

Broad band IF systems are required for sensitivity reasons and early digitization of the IF signal should be considered. Fibre optic transport of the signals (IF and local oscillator) should be studied.

4.4. CORRELATOR

The correlator is a major item in the study. The new fast correlator chips should be evaluated and manufacturers identified; a comparison with more units using slower chips should be carried out. The question of separate line and continuum correlators should be addressed. The need for a special chip development and development of fast samplers must also be considered.

4.5. ATMOSPHERIC PHASE COMPENSATION

A crucial aspect of the study will be the development of a method to correct the interferometer phases for atmospheric fluctuations. Several schemes have been suggested, but the most promising results have been recorded at IRAM, as reported by Welch at this meeting. The method used is that originally put forward by Wright and Welch (1990) and is to monitor the variation in sky brightness temperature in the direction of observation, preferably with a total power channel in parallel with the receiver used for observations. The brightness temperature variation is proportional to the water vapour fluctuation in that antenna beam and can be used to correct the phase. The method requires high receiver stability (1 part in 10^5), which is not usually achieved in today's millimetre wave receivers. This, and other phase compensation techniques will be studied using the IRAM interferometer.

5. International Collaboration

A large array will be expensive but not excessively so, compared with current optical telescope projects or small scientific satellites. There may even be significant savings through mass production of receivers and antennas. However, in this meeting we will hear about three array projects, all of which favour a Chilean site, and whose combined cost is more than one billion dollars. This is a high cost to astronomy and it must make sense to try to collaborate internationally to fund and build an array which is acceptable to all parties. The Millimetre Array Working Group set up by URSI and now co-sponsored by IAU is an appropriate forum to discuss the compromises and advantages of a collaborative project.

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