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Origins of the Molonglo Radio Observatory —The Cross and the MOST*

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Abstract

The history of the Molonglo Radio Observatory is reviewed from initial steps in 1960 through the construction of the Cross and its conversion to the MOST. Some of the problems are discussed and the reasons behind various design decisions are explained. A selection of early scientific programs carried out with the Cross is briefly described.

1. First Steps

By 1960 the seminal work in radio astronomy had been completed in Australia, England and the USA. The era of cheap and relatively simple instruments was over and large radio telescopes were being planned or under construction throughout the world. In Australia, and indeed in the whole southern hemisphere, there was only one major centre for radio astronomy, the Division of Radiophysics in CSIRO. Here a large general purpose reflector was under construction (at Parkes), primarily to extend the galactic and extragalactic work, while a large 'radioheliograph' was planned to extend the solar work. Even with funding from US agencies and the Australian government these instruments were stretching the resources of the Division to the limit and there was no immediate prospect of other significant developments.

As a result of my experience with the Cross radio telescope, which I had invented and used during the 1950s, it seemed inefficient to use the extremely flexible Parkes radio telescope for bread-and-butter survey purposes; such use would limit the time on the kinds of programs at which it would excel. More logical would be the construction of a second generation Cross which could provide better resolution and sensitivity for survey purposes at a fraction of the capital and running costs. However, this seemed impossible within CSIRO and I spent some time sounding out various universities about the feasibility of their entering the radio astronomy field and backing my construction of such an instrument. My efforts bore no fruit until Harry Messel came to the party.

For some time Messel, the head of the School of Physics at Sydney University, had been planning to build up an optical astronomy group under

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the leadership of Hanbury Brown who was to construct a large version of his Intensity Interferometer to measure the diameters of many stars. Along with this unique program, a reasonably large optical telescope was to be acquired and operated by Colin Gum, a recent graduate from Mt Stromlo. However, Gum was killed in a skiing accident while holidaying in Switzerland and, knowing of the problems of funding in Radiophysics, Messel decided to make a bid for a radio astronomy group as well, offering the funds set aside for the optical telescope which might come later, if necessary. The funds for these and other projects Messel was launching were largely provided by the then Nuclear Research Foundation, a private funding organisation which he had founded shortly after his appointment at Sydney University in 1952. This offer which totalled $200,000 was just what was needed and I joined the School of Physics in June 1960 with the aim of building up a radio astronomy group and constructing a large 'Cross'.

Design work began immediately while the group was slowly built up, first Arthur Watkinson followed by Alec Little, both colleagues of mine from Radiophysics, then in the following years, Bruce McAdam and Tony Turtle, recent graduates from Cambridge, and Michael Large from Jodrell Bank. Thus the major radio astronomy centres of the time were all represented. Students (honours year, M.Sc. and Ph.D.) were also recruited for work on instrumental design and testing and later on, in many cases, as construction workers on the radio telescope itself. A specialist workshop group was also built up.

Very important too was the almost immediate formation of a 'Radio Astronomy Centre' for collaboration between the Schools of Physics and Electrical Engineering (Messel 1960). This came about because Chris Christiansen, a former colleague of mine in Radiophysics had recently taken a chair in electrical engineering at Sydney University, leaving Radiophysics as a direct result of the political turmoil associated with the Parkes radio telescope. Many aspects of the proposed Cross were of great interest to the engineering staff and they were keen to cooperate, eventually taking over the design and construction of a large part of the receiver system. A few years later they became involved in the development of their own radio telescope.

2. The Cross

From the beginning there seemed to be few problems in constructing a Cross within the available budget of $200,000 which would be able to survey the sky at metre wavelengths with a sensitivity and resolution at least equal to that anticipated for the Parkes radio telescope operating at its optimum wavelength. But why stop there? Harry Messel was very enthusiastic about the whole project and had approached many of his contacts among the funding agencies in the USA. He learnt that their National Science Foundation was considering a departure from its policy of funding only US universities and that outstanding applications from overseas universities were likely to be considered. This was our chance. Immediately I prepared and submitted a detailed proposal, based on the design and experimental work carried out until then, for a Cross which would substantially outperform the Parkes radio telescope but still be within the bounds of likely funding from the NSF. This would not only be a survey instrument but would permit rapid declination changes for a variety of observational programs.

The proposal was submitted during 1961 and began as follows: 'Advances in radio astronomy now require the construction of radio telescopes of very large size. The smaller countries will find it increasingly difficult to provide financial support on a suitable scale and there is a real danger that the largest instruments will be concentrated in the northern hemisphere among the few nations able to afford them. Thus radio astronomy is likely to find itself in the same situation as optical astronomy in which many interesting and significant problems cannot be properly tackled because of the lack of suitable instrumentation in the southern hemisphere. It was with the idea of mitigating this situation that plans have been made for the construction of a very large and sensitive radio telescope in Australia. Already this country has under construction, and in fact nearly complete, a general purpose reflector of the steerable parabolic dish type having a diameter of 210 feet and capable of operating down to a wavelength of 10 cm. It is proposed that an additional instrument be constructed which shall be substantially more sensitive and have higher resolution; also it is to operate at lower frequencies ... a cross-type instrument is planned.'

The push for a more powerful instrument than the Parkes radio telescope became known at Radiophysics and a letter was sent to the NSF condemning the proposal and suggesting that to support it would be 'money down the drain'. However, US referees supported the proposal unanimously and to resolve the matter the then head of the NSF astronomy section, Geoffrey Keller, paid a brief visit to Sydney to interview those concerned and inspect the facilities of the School of Physics. We passed the test and received the support I had requested, but a bad taste was left which soured relations with Radiophysics for many years to come. Instead of complementing each other the two radio telescopes were effectively in competition with, of course, Parkes having a substantial head start.

When I joined the School of Physics one of the first things to be done was to find a suitable flat area to construct a large Cross. With Arthur Watkinson I had investigated several locations on the Sydney plain before deciding reluctantly that we must go further afield. We eventually decided on the present area near Bungendore which was ideal for our purposes. Although far from Sydney it was close to the facilities and astronomers of ANU and Mt Stromlo Observatory, but well shielded from Canberra's electrical interference. I knew of the area because it had earlier been considered as a possible site for the Parkes radio telescope but was rejected on various grounds. After receiving the NSF support, work began at the site in late 1962; it was named the Molonglo Radio Observatory. Although not exactly on the banks of the Molonglo river it was only a few kilometres distant.

The state of the project in 1962 has been described by Mills *et al.* (1963); details were provided of the planned instrument and its expected performance. It was to be an east–west, north–south Cross with overall dimensions 1 mile × 1 mile. The basic design had been finalised by then and it was later carried through to completion virtually unchanged, except for one important point. Originally two frequencies had been proposed, the principal one at 408 MHz, at which the beamwidth would be 2.8 arcmin, and a second lower frequency of 110.5 MHz required to provide spectral information for the brighter sources. However, before the north–south feed system for the second frequency was

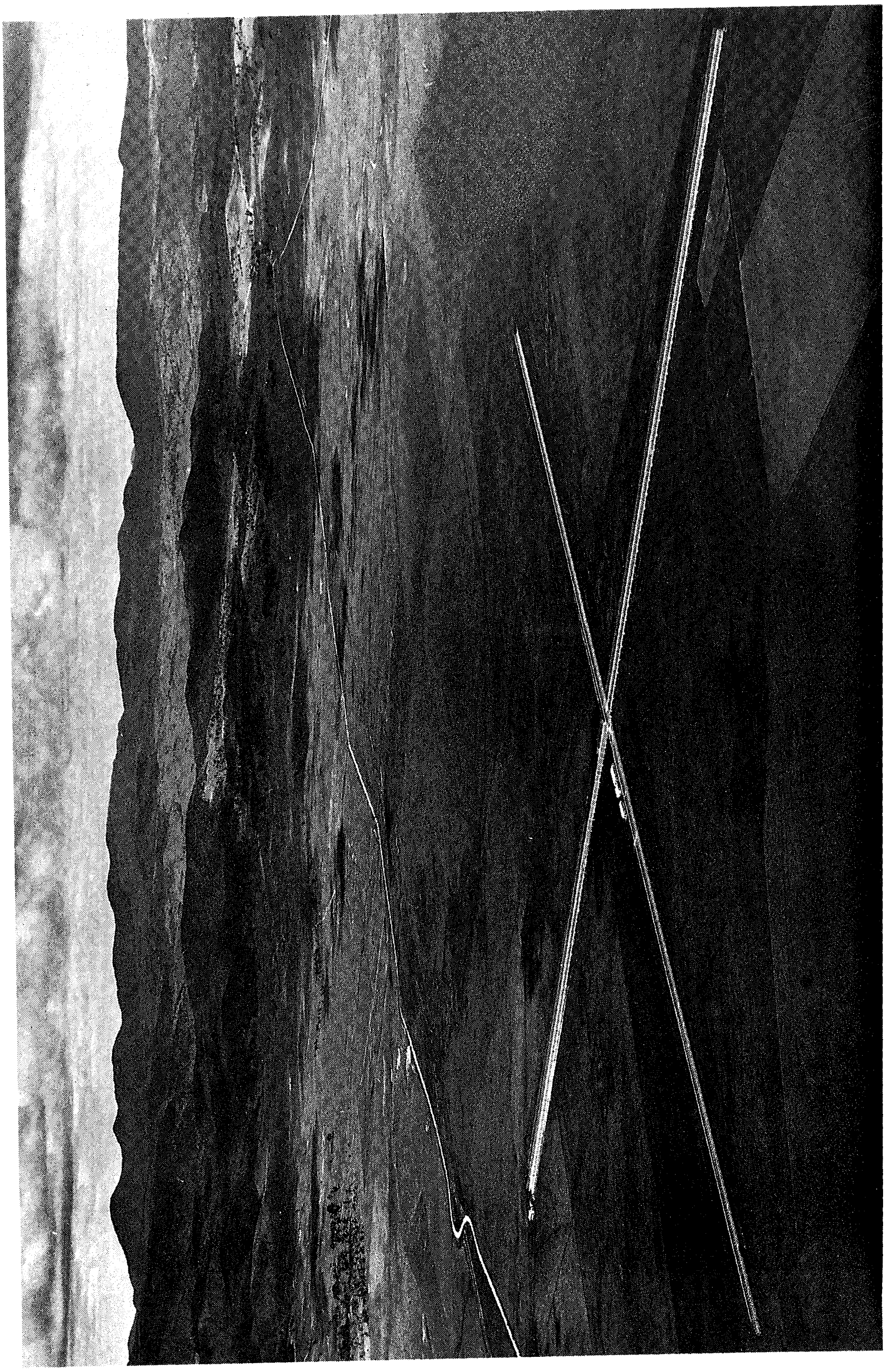

Fig. 1. The 1 mile Cross at the Molonglo Radio Observatory in 1968.

installed, it was realised that the solar radioheliograph then being constructed by CSIRO could be adapted for studying radio sources at low frequencies with greater effect. In view of the pressures which were building up on our facilities at the time it therefore seemed wise to conserve resources and not proceed with the full 110.5 MHz system. The east–west arm alone was eventually used for some limited observations.

Once begun, the construction of the 408 MHz Cross proceeded smoothly, if rather more slowly than hoped. The east–west arm was completed by 1965 and used for the first observational paper to be published (Mills and Glanfield 1965) while installation of the rather complex feed systems for the north–south arm continued. This seemed the appropriate time for an official opening ceremony which took place in November 1965 with prime minister Menzies doing the honours. In addition to a collection of local dignitaries there was a strong US contingent at the ceremony including the ambassador and representatives from the NSF and Cornell University with whom Messel had recently been instrumental in organising the Cornell–Sydney University Astronomy Centre.

After this brief but necessary interlude the work of installing the north–south feeds and receiver system continued until the full Cross came into operation in 1967 (see Fig. 1). By this time the Parkes radio telescope had been launched into full scale surveys of the southern sky so the Molonglo sky survey, although begun immediately, was continued as a rather low key activity; it was recognised that our survey results must follow and improve on those from Parkes with better positions and deeper surveys.

Several programs had already begun with the east–west fan beam system and these were continued, mainly by students, using the new pencil beam data as they became available. Objects studied included supernova remnants, HII regions, nearby bright galaxies including the Magellanic Clouds, radio galaxies, clusters of galaxies and, of course, searches for radio source identifications with galaxies and quasars. These were the programs on which the Observatory has developed and on which many students later cut their teeth, but even then the sensitivity, resolution and pointing accuracy of the Cross was sufficient for substantial advances. These cannot all be described here but two of the early programs stand out in my mind.

The first is an unexciting one but vital for the study of thermal emission at low frequencies, the establishment of an absolute flux density scale. Using a technique developed by Alec Little for the original CSIRO Cross at 85.5 MHz a Ph.D. student, David Wyllie, used the east–west arm to establish the absolute flux densities of a large selection of relatively weak radio sources at 408 MHz (Wyllie 1969). This and the earlier 85.5 MHz scale have been the only successful attempts to establish a scale of absolute flux densities in the southern hemisphere and both have stood the test of time—particularly the 'Wyllie scale' which by now has been thoroughly tested by transferring from northern hemisphere data.

The other program that stands out is the first collaboration between Molonglo and Parkes which was left to a Canadian and an American to organise, Peter Shaver, a Ph.D. student at Sydney University and Miller Goss, a research fellow at Radiophysics. By 1968 it had been found possible to extend the operating frequency of the Parkes radio telescope to 5 GHz ($\lambda = 6$ cm) where its resolution and sensitivity (for thermal sources) was not much inferior to the Molonglo Cross. A survey of a large number of galactic sources at the two widely separated frequencies of 408 MHz and 5 GHz provided a real breakthrough in the identification of HII regions and supernova remnants and in studying their physical properties (Shaver and Goss 1969). This was the prototype for several other fruitful collaborations in later years.

In the course of the next ten years the sensitivity of the Cross was steadily improved and a survey of the whole accessible sky (to declination +18·5°) was eventually completed to a low flux density level; the complete output data for this survey have been retained on magnetic tapes. Several catalogues were published, the most comprehensive and accurate being the 'Molonglo Reference Catalogue' of the brighter sources (Large *et al.* 1981) which extends to a flux density of 0·7 Jy and is statistically complete to 1 Jy; it contains more than 12 000 radio sources. Also published were many smaller catalogues of restricted areas including the galactic plane omitted from the Reference Catalogue. Most of these were much 'deeper' than the Reference Catalogue, some extending down to 50 mJy. Altogether, more than 15 000 radio sources have been catalogued and, of course, a much greater number remains on the tapes if needed. Apart from the Reference Catalogue the most important is probably the 'Molonglo Catalogue 4' (Clarke *et al.* 1976) of an area including the Magellanic Clouds. This was responsible for the discovery of many supernova remnants in the Clouds and was the best available collection of radio maps of the Cloud sources until the surveys with the MOST described later.

All these programs were anticipated when the Cross was first designed but perhaps the most notable achievement was in a completely unexpected direction. The discovery of pulsars by the Cambridge group in 1968 led to a world-wide flurry of activity. At Molonglo, Tony Turtle undertook to search in the southern sky using the fan beam of the east–west arm and promptly discovered two (Turtle and Vaughan 1968), but then had to depart for an overseas commitment. Michael Large took up the search and almost immediately found the Vela pulsar within the confines of a supernova remnant and with a period of 0·09 s, very much faster than any known until then (Large *et al.* 1968). Shortly afterwards an even faster pulsar was shown to be within the Crab Nebula using Cornell University's giant reflector at Arecibo and the only reasonable explanation in terms of spinning neutron stars became generally accepted.

The east–west arm of the Cross proved to be a very effective detection system for pulsars; quite accurate positions could be obtained, particularly if the north–south arm was used to measure the declination, but because of the limited observation time not much in the way of physical properties could be measured apart from the dispersion measure, pulse shape and rough period. By the time the initial sky survey was completed in mid 1969 some 31 pulsars, more than half the total known, had been found at Molonglo but little further work was done until 1976 when a collaboration between Molonglo and Parkes was proposed by Dick Manchester of the Division of Radiophysics. He proposed that at Molonglo a further search survey be carried out using sophisticated computer analysis techniques which had been developed in the intervening years, together with a more sensitive receiver system which Radiophysics would provide. Follow-up observations for confirmation and to obtain more accurate declinations, dispersion measures and periods would then be carried out at Parkes, taking advantage of their tracking capability. This survey, was most successful and resulted in more than doubling the number of known pulsars from 149 to 304 (Manchester *et al.* 1978). It was the last major program at Molonglo before shutting down the Cross.

3. The MOST

From the beginning it was realised that the Cross would have a rather limited useful life. Once the whole sky had been surveyed there would be a rapid fall-off in scientific returns even allowing for the substantial improvements in sensitivity and data handling which were likely. To maintain a strong scientific program some major changes of instrumentation would be needed. First thoughts were that a change of frequency to 1420 MHz and perhaps the provision of facilities for H-line observations would be the answer; the mechanical specifications of the Cross were chosen so that this upgrade would be feasible, if expensive. It was clear that one of the major technical problems would be the construction of a phased north–south feed system. A suitable design occurred to me, employing a novel form of a very cheaply produced circularly polarised feed. Experimental work showed that it was perfectly feasible (Mills and Little 1972) but I soon began to have doubts about the real usefulness of a Cross operating at 1420 MHz in the face of instrumental developments in the School of Electrical Engineering (the Fleurs Synthesis Telescope) and the proposal for a synthesis telescope which was being floated at Radiophysics. The Cross of course was a transit telescope with sensitivity limited by short observation times despite its large collecting area.

Eventually I realised that the east–west arm of the Cross could itself be easily turned into a synthesis telescope by multiplying the east and west arms together, providing multiple fan beam outlets and using the phased feed system we had developed, together with the existing tilting mechanism, to track a region for 12 hours. This was obviously the answer: in view of the length and collecting area of the east–west arm, neither of the other instruments under development or proposed then would have a comparable performance at 1420 MHz. There were some problems, however. Technically, the stability of the receiver pass band might prove inadequate for spectral line work because of the use of phased feeds. Politically, obtaining the necessary funds would be a nightmare; the NSF was no longer funding foreign universities, it would be too expensive for the Australian Research Grants Committee, our normal source of operational funding, and specific governmental assistance could be ruled out if CSIRO was also pressing for a synthesis telescope. In these circumstances there seemed no alternative but to abandon 1420 MHz in favour of a much cheaper and easier lower frequency project which could realistically be funded by the ARGC and was well within the capacity of the radio astronomy group to carry through quickly.

A set of possible operating frequencies was defined by the resonant modes of the existing east–west waveguide feed system. Initially 803.5 MHz was chosen but after some discussion with the frequency allocation authorities the frequency of 843 MHz appeared to be more easily protected from interference. Experimental work began on converting the 408 MHz east–west feed system to a circularly polarised phased feed at the new frequency using a design similar to that already developed for 1420 MHz. At the same time a computer simulation was carried out of the synthesis operation and of the effects of the likely errors in phase and gain known from experience with the Cross. It was concluded that the whole project was eminently feasible (Mills *et al.* 1976), the ARGC supported our application for funds, the Cross was finally closed down in 1978 and the mechanical conversion began.

There was some discussion at first of another possible receiver system in which the separate outputs from the 88 preamplifiers disposed along the antenna would be combined in pairs to form the interferometers of a conventional synthesis system. This would permit better control of phase and amplitude errors and undoubtedly lead to a better dynamic range but there were a number of drawbacks, most obviously a loss of sensitivity unless 44^2 interferometers were formed, with the associated rather horrendous computing requirements. In any case there would be a vast increase in computer needs and almost certainly a very much longer time to become fully operational. We decided to stay with an analogue system which had the undoubted advantage that the results of an observation would be immediately available and the added advantage of making maximum use of the available collecting area for the detection of transient signals such as pulsars.

By early 1981 the conversion was essentially complete, the first fan beam observations had been made and the whole system was described (Mills 1981). By mid 1981 the first synthesis maps were produced and the scientific programs began. The Molonglo Cross had been replaced by the MOST (Molonglo Observatory Synthesis Telescope).

Despite the use of analogue techniques which allowed real time synthesis, the final production of a map did require rather sophisticated computing which caused some problems. Fortunately no 'cleaning' of the maps was necessary for the early programs because the directly synthesised beam was relatively clean and publishable maps could be produced shortly after the 12 hour observations ceased. This 'raw' beam was used for much of the early work, particularly for the very successful searches for supernova remnants in the Magellanic Clouds, starting with the SMC, the first major program of the MOST (Mills *et al.* 1982). Further developments, results and future prospects are described elsewhere (see e.g. Robertson 1991; present issue p. 729).

To conclude, the original investment by Harry Messel and the Nuclear Research Foundation of $200,000 to begin a radio astronomy program has led to a very successful outcome. Major contributions to astronomy have been made over the years at the Molonglo Radio Observatory and many students have been launched on successful careers. It seems likely that the Observatory will continue to provide an important input to astronomy for many years to come.

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