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The structure of radio sources–the Molonglo papers

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Abstract

The Molonglo Cross Radio Telescope was the last of three remarkable interferometers built by Bernard Mills. Built between 1961 and 1967, it improved both resolution and sensitivity by an order of magnitude over the Fleurs Mills Cross and all contemporary parabolic telescopes. In its operation over 11 years to 1978 it made definitive surveys of both galactic and extragalactic sources in the Southern sky. Richard Schilizzi, whose career was celebrated at this conference, began his radio astronomy at Sydney University in 1967, the year that the Molonglo Cross telescope made its first pencil beam observations. This paper describes the history of the Cross telescopes, and the research by the Sydney group up to the departure of Richard to Caltech in 1973 and the dismantling of the Cross in 1978.

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[1] Speaker

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1. Early Interferometers

The first radio interferometer observed from the cliff at Dover Heights in 1945-1948 and is well described by Miller Goss in this issue. (It is appropriate to note that the 1948 observations from NZ cliffs at Leigh and Piha by Bolton and Stanley will be celebrated in January 2013 by a conference at Leigh - which is near the NZ site of an SKA element at Warkworth). Subsequent telescope developments in Northern observatories have been recorded by Woody Sullivan in his highlights of interferometry in early radio astronomy (1988), but he does not mention later innovations in Sydney. He does end his review by stressing the influence of J.A. Ratcliffe's lectures on Fourier concepts. Ratcliffe shaped the thinking of many astronomers (Pawsey, Bragg, Bracewell, Ryle, Smith, Scheuer) through his teaching and this brought parallel developments at observatories in both hemispheres.

The early telescopes had beamwidths measured in degrees and eventually arcminutes, unlike the current interferometers with milliarcsecond, or the VLBI nets with microarcsec resolution. However, the basic principles are still the same. Any interferometer brings separate parts of a wavefront together and correlates them in pairs. Each correlation samples the wavefront to give a Fourier component of the source image. An interferometer is a filter of the information in the wavefront. In 1949 Pawsey suggested that Bernie Mills investigate the newly discovered discrete radio sources, but not by using low elevation observations with the cliff interferometer: "The future lay with the use of horizontal baselines" (Mills 2006). Mills' first interferometer at Badgerys Creek spaced 3 bedstead elements at a short and a long separation. His survey catalogued 77 discrete sources and noted that many were resolved, even at this moderate baseline.

Mills realized that a new survey would require more sensitivity, greater EW and NS spacings, yet must also keep the low uv spatial frequencies to observe large diameter sources. He decided to cross correlate two long, thin arrays intersecting at right angles - a cross interferometer - to produce a pencil beam. His idea faced strong scepticism, and he had to prove the concept with a 36m cross in 1953. With funds approved, he built the Mills Cross in the West of Sydney at Fleurs with Alec Little in 1954. This gave a pencil beam of 50 arcmin at 85 MHz, matching the resolution obtainable at decimetre wavelengths by dishes. In a cross interferometer, the length of the arms determines the resolution and their width independently determines the area and hence the sensitivity. Mills matched these separate parameters to the source density expected in the sky. The survey made by Mills, Slee and Hill between 1955 and 1958 was the first complete survey of the southern sky and their MSH catalogues listed 1159, 892, and 219 sources in three zones of declination. The MSH catalogues listed both large diameter (mainly Galactic) and unresolved (mainly extragalactic) sources. They also made a contour map of the galactic plane over a 10 degree zone for 150 degrees of longitude across the Galactic Centre. Despite this success, the CSIRO abandoned array telescopes except for the solar heliograph at Culgoora. The building of the giant radio telescope at Parkes absorbed all available funding resources.

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2. The Molonglo Cross

In 1960, Christiansen and Mills moved from CSIRO to the University of Sydney, Chris to the Chair of Electrical Engineering and Bernard to lead an Astrophysics Group in Physics. They recruited experienced staff from across the world. Mills was joined in 1961 by Arthur Watkinson (Sydney), Alec Little (Sydney and Stanford) and Bruce McAdam (Cambridge). Robert Frater was enticed back from industry to the Electrical Engineering Department to develop solid state receivers and IF stages for the Molonglo Cross. In 1963 Michael Large (Jodrell Bank) and Tony Turtle (Cambridge) joined the team.

With a major grant from the US National Science Foundation, this group built an ambitious mile cross telescope between 1961 and 1967. The two arms were 1.6 km long parabolic cylinders, 12 m wide giving an effective area of 19 000 sq m for the pencil beam interferometer. The EW arm was built first, and began observing in 1964 with a 1.6 arcmin fan beam. The NS arm was much more complex, as 4248 dipoles each required phase and delay settings for an observation at any of 800 declinations, but by September 1967 the arm was ready. The Molonglo Cross began observing at 408 MHz with a noise of 16 mJy using 11 simultaneous pencil beams of 2.86 arcmin that spanned a 15 arcmin zone of declination. In 1967 it was the second largest radio telescope, exceeded only by the northern Arecibo telescope.

The major task for the Cross was a survey of the sky south of declination +18. For this project, the declination was fixed for a scan of 17 hours in right ascension. However, a point source transited a pencil beam in 15 seconds, and with a minute of sky baseline plus calibration, an individual observation was completed in less than 2 minutes. A sequence of up to 250 sources could be observed in 24 hours with an occasional change from far south to a positive declination at 5 degrees per minute giving time for a rest or a meal. Staff and students shared 3-5 day observing sessions, each student given priority for a particular class of source as their thesis study. At other times, the survey ran overnight, monitored by the observatory manager. All data was recorded on digital tape and then taken to Sydney for computer analysis.

The Cross observed for 11 years up to August 1978, when it was switched off and over the next three years converted from 408 MHz to 843 MHz as the MOST - the Molonglo Observatory Synthesis Telescope (McAdam 2008). During this time the 408 MHz data were checked, sources verified, optical identifications sought, and the Molonglo Reference Catalogue was finally published in 1981 with 12015 sources listed on microfiche.

3. Observations of source structure

Mills led the group until his retirement in 1985. During his 25 years at Sydney University, he mentored 22 PhD students 18 of whom continued to a professional career in astronomy. Most students had been Sydney undergraduates, but some were attracted from other universities by Mills' reputation. In particular, Richard Schilizzi came from Armidale after an honours BSc at the University of New England. Peter Shaver came from Canada, Anne Green from

Melbourne, and Gordon Robertson from Adelaide. These were among the group of 15 PhD students who observed with the 408 MHz Cross between 1964 and 1978. Twelve of them are active in astronomy around the world, but sadly, Bob Munro who came to Jodrell Bank as a postdoc died soon after arriving in England.

Richard Schilizzi joined the Molonglo group in 1967 just as calibration and exploration with the Cross began. He was one of five who studied the structure of various classes of radio sources for their theses. Michael Kesteven, Peter Shaver and Anne Green observed sources in the Galactic Plane. James Clarke mapped the Magellanic Clouds and Richard Schilizzi observed the structure of sources in the rest of the extragalactic sky. All five were supported by colleagues working on calibration of flux density, positional calibration and optical identifications. The fundamental project by David Wyllie established the absolute flux density scale at 408 MHz by building a standard dipole of calculated gain and observing five strong sources in three interferometer pairs: East arm * dipole; dipole * West arm; East arm * West Arm. Since the East and West arms were identical, these three correlations gave the absolute gain of the EW fan beam and thus the 408 MHz flux density in Jansky of southern sources. John Sutton, Robert Munro and Richard Hunstead provided the Cross with accurate position calibrators, tying their radio positions into the optical frame with optical identifications. Table 1 lists the students, the date of thesis submission, the number of papers they published and their thesis title.

Table 1 The fifteen Sydney PhD students who used the Molonglo Cross 1967-1978, showing their thesis title and number of papers published on their work.

PhD student	Submission	Papers	Thesis Title
John Sutton	Nov 1966	3	The Determination of the Positions of Radio Sources.
Michael Kesteven	Jan 1968	5	Radio Observations of Some Supernova Remnants.
David Wyllie	Sept 1968	2	An Absolute Flux Density Scale at 408 MHz.
Peter Shaver	1970	14	Radio Emission from Galactic HII Regions.
Malcolm Cameron	Sept 1970	8	Radio Observations of Bright Galaxies.
Trevor Clarke	Aug 1971	3	The Measurement of the Angular Sizes of Radio Sources by Model Fitting.
Robert Munro	Aug 1971	9	Identificationsof Radio Sources from the Fourth Cambridge Catalogue.
Richard Hunstead	May 1972	14	Studies of Selected Radio Sources.
Anne Green	Sept 1972	7	Spiral Structure of the Galaxy from a Radio Continuum Survey.
Richard Schilizzi	Nov 1972	8	Structures of Extragalactic Radio Sources.
Alan Vaughan	May 1974	18	Pulsar Observations at Molonglo.
James Clarke	May 1974	7	A High Resolution Survey of the Magellanic Clouds at 408 MHz.
Robert Milne	Jan 1976	3	Interplanetary Scintillation at 408 MHz.
Michael Batty	Feb 1976	3	Low Frequency Recombination Lines.
Gordon Robertson	Dec 1976	10	Radio Source Surveys at 408 MHz.

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4. The Molonglo papers by Richard Schilizzi

Richard's task was to find resolved extragalactic sources and establish their typical structure. This project was contemporary with similar northern surveys at low frequency: the Cambridge 1-mile synthesis telescope mapped 82 northern sources at 408 MHz with an 80 arcsec beam, and the 6C survey observed many of these at 150 MHz with a 4 arcmin beam. Richard mapped 116 sources from +18 to -80 declination after a search of 400 candidates listed in the Parkes catalogues or unpublished lists from the advancing Molonglo survey. He then took the centroid and peak positions of the extended radio sources, and searched the fields on the Palomar Observatory Sky Survey for optical identifications. The optical paper (Schilizzi, 1975) gave positions for 234 objects in 86 fields, calibrated by hundreds of reference stars to achieve rms errors of better than 0.5 arcsec in each coordinate. Two southern fields did not have optical plates but 114 fields yielded 34 new identifications, confirmed 44 previous IDs, left 7 possible for later study, and there was blank sky in 29 fields to the limit of the Schmidt Sky Survey.

Table 2 Resolution of Contemporary Radio Telescopes in 1964-1978

			baseline/ wavelengths
Molonglo	408 MHz	EW Fan beam	0-2130
		Cross Pencil beam	0-1065
Parkes	408 MHz	interferometer	190- 665
	1401 MHz	interferometer	570-2000
Cambridge	408 MHz	one-mile synthesis	0-2040
Owens Valley	1425 MHz	interferometer	0-2300

Students were encouraged to present papers at the annual science meetings of the Astronomical Society of Australia. Richard published two such papers - in 1969 and 1970 - on the structure of some unusual sources found in his early observations. His next three papers were collaborations with other groups on the spectral structure and identification of extended sources. Richard's time at Sydney ended in Nov 1972 with the completion of his PhD thesis - "Structures of Extragalactic Radio Sources", and he moved to a postdoctoral position at Owens Valley, Caltech in 1973 for three years. During this time, he completed the two major papers that formed volume 79 in the Memoirs of the RAS (essentially his thesis survey). An eighth Molonglo paper, written in Dwingeloo described the puzzling low-brightness relic source 1401-33. These Molonglo papers are numbered 1-8 in the references. Richard's 17 further papers during 1973-1977 were concerned with VLBI and milliarcsec structure and should be described by others. We at Molonglo are proud to have started him on his astronomical career.

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