

UNDERSTANDING OUR GALAXY - KEY CONTRIBUTIONS FROM THE PARKES TELESCOPE.

J. L. CASWELL

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ABSTRACT

Young massive stars, with their spectacular masers and HII regions, dominate our Galaxy, and are a cornerstone for understanding Galactic structure. I will highlight the role of Parkes in contributing to these studies - past, present and future.

Subject headings: Masers — high mass stars — Galactic structure — Parkes radio telescope

1. INTRODUCTION

On the first day of our symposium. the contributions were entertaining and knowledgeable reflections on the early years at Parkes - chiefly recalling an era from which there are few pioneers left with personal experience. Subsequent days focus on active work still continuing at Parkes. I am pleased to be the bridge from the past to the present, especially to the next session of the symposium, dealing with current studies of young massive stars and their masers.

My main theme will be to show how the Parkes studies of masers and related objects contribute to revolutionizing the picture of our Galaxy, its content and its structure.

2. GALACTIC STRUCTURE

2.1. *An early view*

Radio astronomy, with its ability to see through the dusty disc of our Galaxy, gave us the first quantitative realization of the likely extent of the Galactic disc, and hints of its full spiral structure. The history of these discoveries stemming from the earliest HI observations is beautifully summarized by Oort, Kerr & Westerhout (1958). They present an adventurous first attempt at revealing spiral structure, tempered by an acknowledgment of its very preliminary nature. They also include prescient musings on the likely role of large-scale interstellar magnetic fields influencing the appearance of the spiral arms.

This early picture of spiral structure was largely reinforced by subsequent improved HI observations, and by the newer tool of CO observations, which map the dense molecular clouds that are somewhat more closely related to the expected massive star distribution.

2.2. *Tracers of massive stars, the dominant component of spiral structure*

While the spiral structure of our Galaxy depicted by HI gas was of great interest, the spiral structure seen photographically in nearby galaxies is traced chiefly by a very different population - the hot, young, massive blue stars, and the HII regions that surround them. Optical study of these objects in our Galaxy is impeded by dust and obscuration, so we seek the radio equivalent; the

HII regions, in particular, are detectable from both their radio continuum emission and their recombination line emission (with the corresponding capability of measuring systemic velocities).

2.3. *The value of Parkes for Galactic structure*

Observations between 1.4 and 10 GHz are excellent for the HII measurements, and thus readily pursued at Parkes. This is complemented by another key attribute of Parkes - its southern hemisphere location (with the Galactic Centre passing nearly overhead) and thus accessing the 70 per cent of Galactic disc that is most important for study of its structure.

The systemic velocity of an HII region, measured from its radio recombination lines, is an excellent first start at determining its distance, able to yield a 'kinematic' distance based on a simple rotation curve for the Galaxy. However, the kinematic distances for Galactic locations nearer the Centre than the sun are generally ambiguous, and the ambiguity needs to be resolved by an alternative means. Fortunately, an enhancement to the Parkes dish, the Parkes interferometer, provided a useful discriminator and was being developed at just the right time.

2.4. *The Parkes HI interferometer*

Yesterday, Ron Ekers described the innovative design of the Parkes interferometer and here I will remind you of its modification and novel use by Radhakrishnan to study the HI spectra towards strong continuum sources (Radhakrishnan et al. 1972a). The primary purpose was to measure the properties of absorbing HI clouds; but, as a by-product, for sources in the Galactic plane, it could determine kinematic distances of Galactic sources, as amply demonstrated by Radhakrishnan and Miller Goss (Radhakrishnan et al. 1972b). My first years at Radiophysics overlapped this work, shortly before Rad and Miller both departed from Australia. I was excited at the prospect of getting more distances - a project that would be abandoned if I did not adopt it. I was blessed to inherit a talented team of engineers (John Murray, Dave Cooke and Doug Cole), complemented by astronomy advice and help from Rob Roger, visiting at that time from Penticton (where we had previously worked together), and fresh from planning an HI interferometer there. Upgrades to the Parkes interferometer allowed us to achieve excellent results, leading to a large number of

distance determinations for Galactic radio sources, both supernova remnants and HII regions (Caswell et al. 1975).

3. NEW SURVEYS OF THE GALACTIC DISC

Progress in mapping the Galaxy had been good, but needed the impetus of new surveys of Galactic radio objects. We chose to survey the Galactic plane at 5 GHz in another ambitious large project. This was conducted with Raymond Haynes, firstly in the continuum (Haynes, Caswell & Simons 1978), and then with a recombination line follow-up (Caswell & Haynes 1987). This greatly improved our assessment of spiral arms in the southern sky, especially the Carina arm.

3.1. *OH and water masers - the early years*

Until now, I have kept to a chronological order, but that eventually becomes impossible in the real world of overlapping events. It seems appropriate to segue into a quote from Dean Kamen: ‘People take the longest possible paths, digress to numerous dead ends, and make all kinds of mistakes. Then historians come along and write summaries of this messy, non-linear process and make it appear like a simple straight line’. More succinct is a related sentiment from Mark Twain: ‘In the real world nothing happens at the right place and the right time. It is the job of journalists and historians to correct that’. Hindsight, even if unintentional, modifies the story. But, overall, in my presentation of the subsequent research, I will try to retain the logic and motivation that drove it.

I now backtrack a few years to show where masers fit into the picture. OH maser research in the early 1970s was taking another step forward, with searches for new masers planned. I was fortunate to be able to join Brian Robinson and Miller Goss in these developments.

How many varieties of OH masers? The sample known so far was now growing to the point of recognising different varieties, one of which was a large population associated with massive star formation (Robinson, Caswell & Goss 1974).

OH masers were certainly fascinating; surely they would also be useful? To answer this question, our intention was to conduct OH survey projects in a prompt and orderly manner but were then interrupted by ‘an opportunity that was too good to refuse’ - an opportunity to observe water masers in the southern sky.

Ken Johnston from the Naval Research Laboratory had a receiver, we had OH targets, and a first round of improvements to the dish surface at Parkes made it a viable instrument at 22 GHz. The sensitivity was adequate for detecting strong maser emission, and the major challenge was a small beamsize above 20 GHz - a valuable property but with associated problems from pointing errors and uncertainties in our target positions - a hexagonal grid search was needed every time (Johnston et al. 1972). Calibration was also a challenge. Ken Kellerman reminded us yesterday of early planet observations at Parkes, noting that these were not subsequently continued. In fact, we found Jupiter to be the solution to our calibration problem, since at that epoch it was a southerly object near declination -20 degrees.

For several years we then conducted unbiased surveys for OH masers in the Galactic disc (e.g. Caswell, Haynes & Goss 1980), with follow-up of water masers (Batchelor et al. 1980). Coincidence of water masers with OH

was a matter of dispute - how closely associated were they? Our position accuracy at Parkes was limited to about 10 arcsec, at which level the coincidence seemed good. To understand their relationship we needed more precise positions. Some of our masers were within reach of the VLA, and Rick Forster convinced me that it could provide a partial solution to our problem.

It was an ambitious project for the VLA when it was scheduled in 1983. For a while, Rick and I had the VLA record for data processing requirements: our experiment lasted only a few days, but we had spectral line data at long baselines for nearly 100 sources, and needed high resolution spectral line cubes. The results amply repaid our efforts, and demonstrated the extremely close association for many pairs, plus the excess of water maser sites compared to OH (Forster & Caswell 1989).

Eventually it was possible to obtain maser positions in the true southern sky, using the Compact Array of the AT. There followed a productive combination of Parkes spectra and Compact Array positions for OH masers, but it was another decade before we could extend the ATCA studies to the 22-GHz water masers.

3.2. *The methanol ‘explosions’*

The discovery of maser emission at 12 GHz was the first of two major impacts by methanol on star formation maser studies. In an abrupt diversion of effort, with an ‘off-the-shelf’ commercial receiver speedily made suitable for Parkes by Kel Wellington, we were able to use our newly-determined OH maser positions to conduct a search for further examples of the newly discovered 12-GHz methanol transition - with considerable success (Norris et al. 1987).

Scarcely had we returned to pick up the threads of the OH and water research when the next methanol impact was upon us - the discovery in 1991 (Menten 1991) of methanol maser emission at 6668 MHz - which was found to usually surpass both OH and 12-GHz methanol in intensity. Once again the agility of Parkes, and our receiver group, was demonstrated, as an excellent new receiver was rapidly deployed and enabled us to reveal the full importance of this transition (Caswell et al. 1995). We finished up with several hundred methanol masers, allowing us to explore the common properties, unusual properties, and even characterise the typical variability, with the first hints of the exciting possibility that some might be periodic variables (Caswell, Vaile & Ellingsen 1995). Periodicity was eventually confirmed in South Africa several years later (Goedhart et al. 2004, 2009). John Whiteoak was a key member of our team and recognised the role that the Compact array could play in methanol studies, despite 6.6 GHz being a frequency outside the nominal ATCA coverage. ATCA accurate positions of the OH and methanol masers then established unequivocally their intimate association (Caswell, Vaile & Forster 1995), with their common source of excitation provided by a massive embryonic central massive star.

4. MORE SURVEYS, AND THEIR PURPOSE

Could those searches for methanol masers be described as a survey? Yesterday, we heard several views on the purposes of surveys, prompted by a presentation from Jasper Wall and Carole Jackson. I have been engaged

in rather a lot of surveys, necessitated by exploring the Galaxy. These are some of my reflections:

The purpose obviously depends on previous knowledge, and the space density of the expected population.

If very few objects are known, then the main purpose may be simply to expand the sample.

If the space density is intrinsically low, much of the importance of a uniformly sensitive large survey is to define the regions where there is nothing!

In a few cases, e.g. a finite Galactic population, we may discover the whole population!

The last point is especially exciting, and seemed applicable to the methanol masers.

4.1. *The MMB survey*

To fully exploit the value of 6.6-GHz methanol masers, we needed a 'proper' survey that was sensitive, had no bias to pre-selected targets, and covered the quite large area of the whole Galactic disc. We questioned whether to use Parkes (necessarily requiring a multi-beam receiver to map with adequate speed and sensitivity) or the ATCA? We chose the best of both options, with Parkes for the survey proper, and the ATCA as an integral part of the project in providing precise positions to arcsecond accuracy.

The Methanol Multibeam (MMB) project proposal to build the receiver was submitted 2001 February, early in the year of the Parkes 40th birthday, with Mal Sinclair as project leader and J. Caswell as project scientist.

It was a collaborative venture with Jodrell Bank, with Jim Cohen leading the UK part. Receiver construction was shared between our two institutions and was ready for testing on the Parkes telescope 2006 January.

Jim Cohen and I had planned the survey strategy and worked intensively together to get the survey running smoothly and productively immediately after 'first light' on Australia Day of 2006. It was a memorable first year of observations, with Jim Cohen present at all our sessions, and Jim's wife Pat welcomed as an additional enthusiastic team member when needed.

Sadly, to our great dismay, Jim died late in 2006, exactly 5 years ago. Over the following few years, we have achieved our goal of completing the survey, and Pat Cohen has been delighted to see these outcomes from the work that consumed so much of Jim's time in the final year of his life; the legacy of the survey is a fitting tribute to his efforts (Green et al. 2009; Caswell et al. 2010).

The outcomes from the survey will be extensive, with many productive follow-ups already completed, and others continuing. There are two areas in particular where the masers have high impact: firstly the far-reaching implications for Galactic structure, where considerable progress has already been made, and which we will return to later; and secondly, the full characterisation of each maser site, by its mass, evolutionary state and environment, and thereby contributing to the ongoing investigation of the poorly understood mechanism of high mass star formation,

5. EXCITED-STATE OH TRANSITIONS AT PARKES

Once again we step back, this time to catch up on the OH maser progress. Although OH maser studies of star formation regions mostly focus on the ground-state

transitions at 1665 and 1667 MHz, the 6035 and 6030-MHz excited-state transitions have recently been recognised as equally valuable, and sometimes more so. For many years, very few telescopes were equipped with a high performance receiver at this frequency. Then Parkes became one of the first telescopes to acquire this capability - using the 6.6-GHz receiver that had recently been purpose-built for methanol studies. It allowed the discovery of many new 6035-MHz masers accompanying 1665-MHz masers (Caswell & Vaile 1995), sparking new interest in the transition. Much rarer is the maser emission from OH in an even more highly excited state, at 13.4 GHz. Again, this is a frequency not commonly covered by high performance receivers on large telescopes. From 1970 until 2002, only one definite maser was known at this transition. Improvements to the Parkes dish surface in 2003 and a receiver of modest performance then provided a combination viable for renewed observational effort, closely following similar renewed efforts at Effelsberg. Parkes was able to detect 8 masers at this transition (Caswell 2004), most of them new and visible only from the southern hemisphere, and increasing the known number to 11, where the total still remains, pending new Parkes observations,

6. PARKES AND ITS ROLE IN SPECTROSCOPY WITH THE LBA

Dave Jauncey and John Reynolds will later describe Australian VLBI more fully, but here I must mention the role of the Australian LBA (Long Baseline Array) in maser studies.

The LBA baselines, from just the three ATNF elements (Parkes, the ATCA and Mopra), extend to 300km, very similar to MERLIN in the northern hemisphere, and allow us to do similar work, but in the richer fields of the southern Galaxy.

Spectroscopy with the LBA was still in the realm of pioneering work in 1998 when we made our first observations of OH masers at 1665 and 1667 MHz. We were able to observe both transitions with high spectral resolution in a single band covering a large velocity range, and simultaneously observing two polarizations. These capabilities were able to solve earlier problems of precise relative positional registration that had plagued earlier VLBI work. The success of this ambitious project owed much to the ingenuity of John Reynolds who coped with each new problem as it arose. The net result was a series of southern OH maser sites mapped at high resolution, and revealing their magnetic fields from the recognition in the spot distribution of Left and Right hand circular polarization of multiple Zeeman pairs (e.g. Caswell & Reynolds 2001 and subsequent papers).

As remarked earlier, OH maser studies of star formation regions mostly focus on the ground-state transitions at 1665 and 1667 MHz, but the 6035 and 6030-MHz excited-state transitions are even more valuable in clearly displaying the Zeeman pairs from which magnetic fields can be inferred. A high performance 6-GHz receiver at Parkes was the catalyst to extend LBA observations to this transition. In this case, it also allowed precise registration of maser spot distributions at 6035 MHz with those of the weaker 6030-MHz transition, in turn identifying Zeeman pairs and magnetic field distributions (Caswell, Kramer & Reynolds 2011).

The success of the LBA in this OH spectroscopy owes much to the large collecting area and high sensitivity provided by Parkes as a key element.

7. THE FUTURE - GALACTIC SPIRAL STRUCTURE, VELOCITY FIELD, AND MAGNETIC FIELD

What does the future look like for Galactic structure, high mass stars and masers?

Preliminary studies of the maser spatial and velocity distribution in the inner Galaxy are already at a stage where they can guide improved Galactic dynamics modelling, since current models are unable to account for the observations (Green et al. 2011), but these are only the beginning of a much greater revolution.

A landmark was achieved in 2006, with a demonstration that VLBI had matured to permit accuracies of better than 0.01 mas (Xu et al. 2006), allowing astrometric parallaxes and precise distance measurements to masers at the Galactic Centre and beyond, extending to the outer edge of the Galaxy (Reid et al. 2009). This achievement with the US VLBA at 12 GHz was shortly matched by similar measurements for 22-GHz water masers (which often accompany methanol masers) using the Japanese array VERA (Honma et al. 2007), and measurements of 6.6-GHz methanol masers using the EVN (Rygl et al. 2010).

So astrometry of masers can now provide a remarkable opportunity to map our Galaxy in detail, to reveal for the first time its precise geometry and velocity field. These are the parameters that must be replicated by a valid dynamical model of the Galaxy. Southern and northern hemisphere telescopes will be needed to acquire the necessary observations and, in these endeavours, Parkes will be a key high sensitivity element in the southern LBA.

Since OH masers are present at about half of the

methanol sites, it will eventually be possible to associate a characteristic magnetic field at each site using Zeeman splitting, and thereby map the magnetic field of the Galaxy, with ‘in situ’ measurements at each site, rather than the line-of-sight average fields that are commonly obtained by Faraday rotation measurements.

8. AFTERWORD

In 1967, the outcomes of a conference held at Charlottesville on the topic ‘Interstellar ionised hydrogen’, were summarised by Gart Westerhout (Westerhout 1968). At that time, the recently detected OH masers were the only known species of astrophysical maser. The role of the masers was uncertain. In Gart’s words:

‘...how relevant are the OH (maser) observations to astrophysics....? Could it be that the emission is a pointer to regions of incipient star formation? Personally, I would say that the OH (maser) study is an extremely interesting intellectual exercise, which should be vigorously pursued, because such exercises lead almost always to completely new developments, and completely new ideas in both theories and techniques. But I don’t think that the OH problem will contribute very much to our further understanding of the interstellar medium at large.’

Has the pursuit of masers over the past 45 years been worthwhile? Perhaps the most emphatic answer is given by the title of a workshop at MPI, Bonn two years ago: ‘Masers: the ultimate astrophysical tools’!

I thank the conference organisers for the opportunity of contributing to this meeting, and expressing my gratitude to many close colleagues who have worked with me in the 40 years that I have enjoyed using the Parkes telescope.

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