Understanding our Galaxy – key contributions from the Parkes Telescope

James Caswell

- Today's session: star formation and masers
- This morning will focus on Galactic studies

Main threads

- Our Galaxy – its contents and structure
- Masers, high mass stars and HII regions
- A link with yesterday – Parkes contributions to these fields over many years
- Recent and ongoing research - looking forward to the later talks

Looking back, looking forward

The past

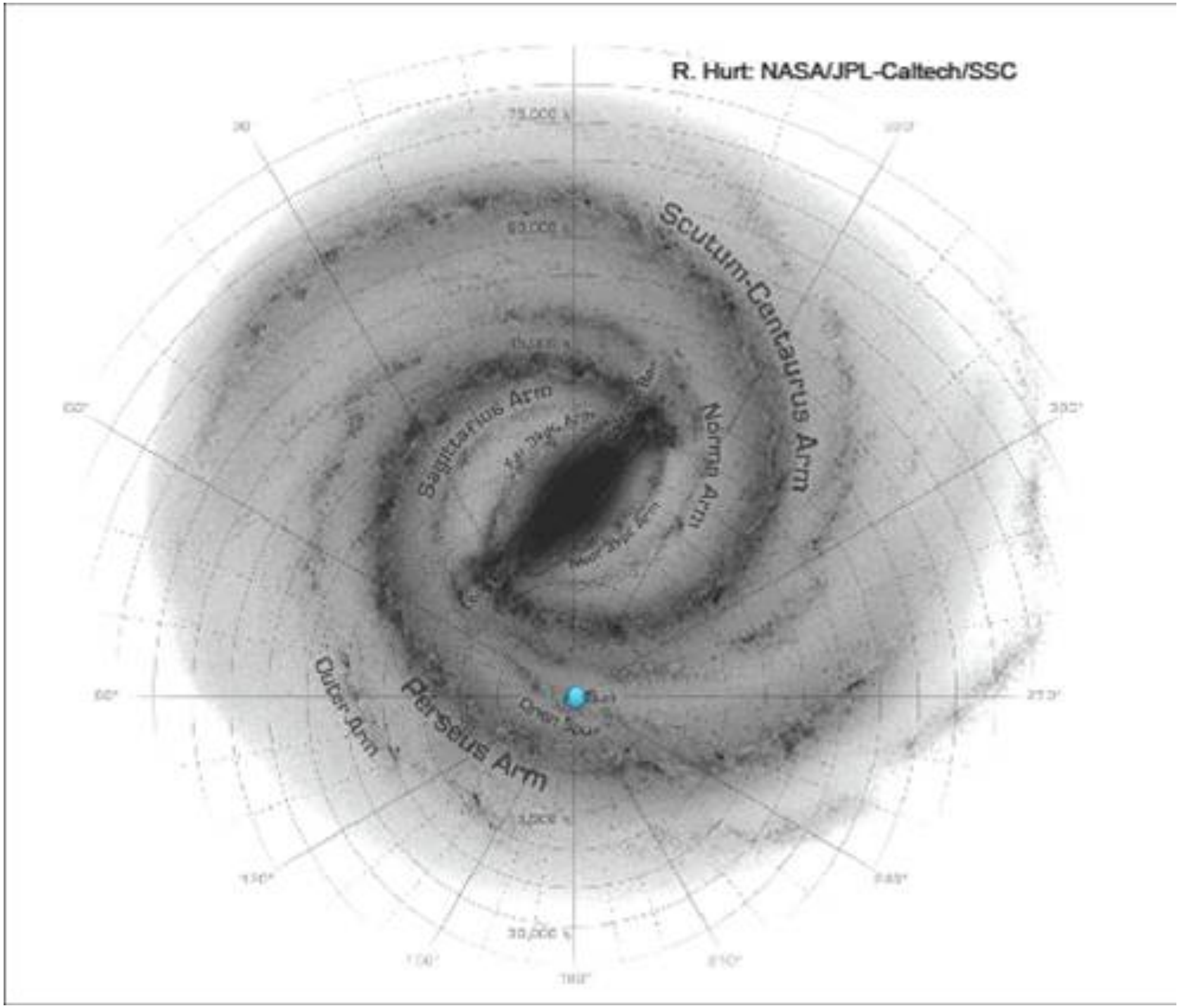
- Firstly, an appreciation to yesterday's speakers for their entertaining reflections on the history.

- We learn from the past:
  ignoring its lessons dooms us to repeat its mistakes
  - and leads us to re-invent the wheel……

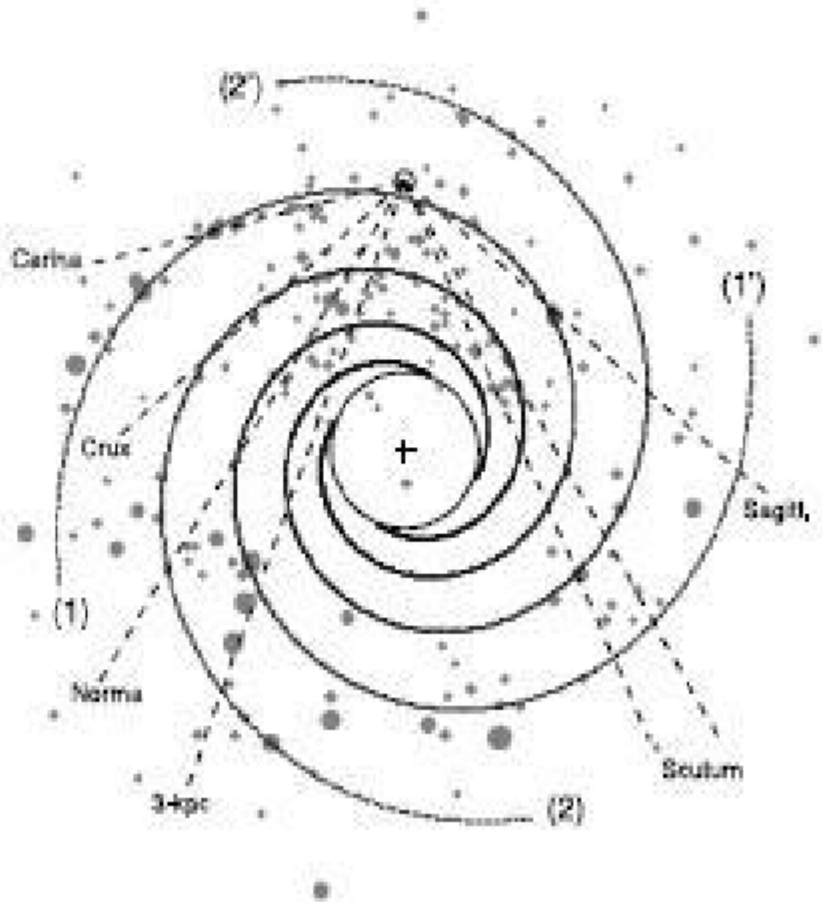
- The corporate memory is fragile –exacerbated by restructuring: Radiophysics - ATNF - CASS

Galactic Structure

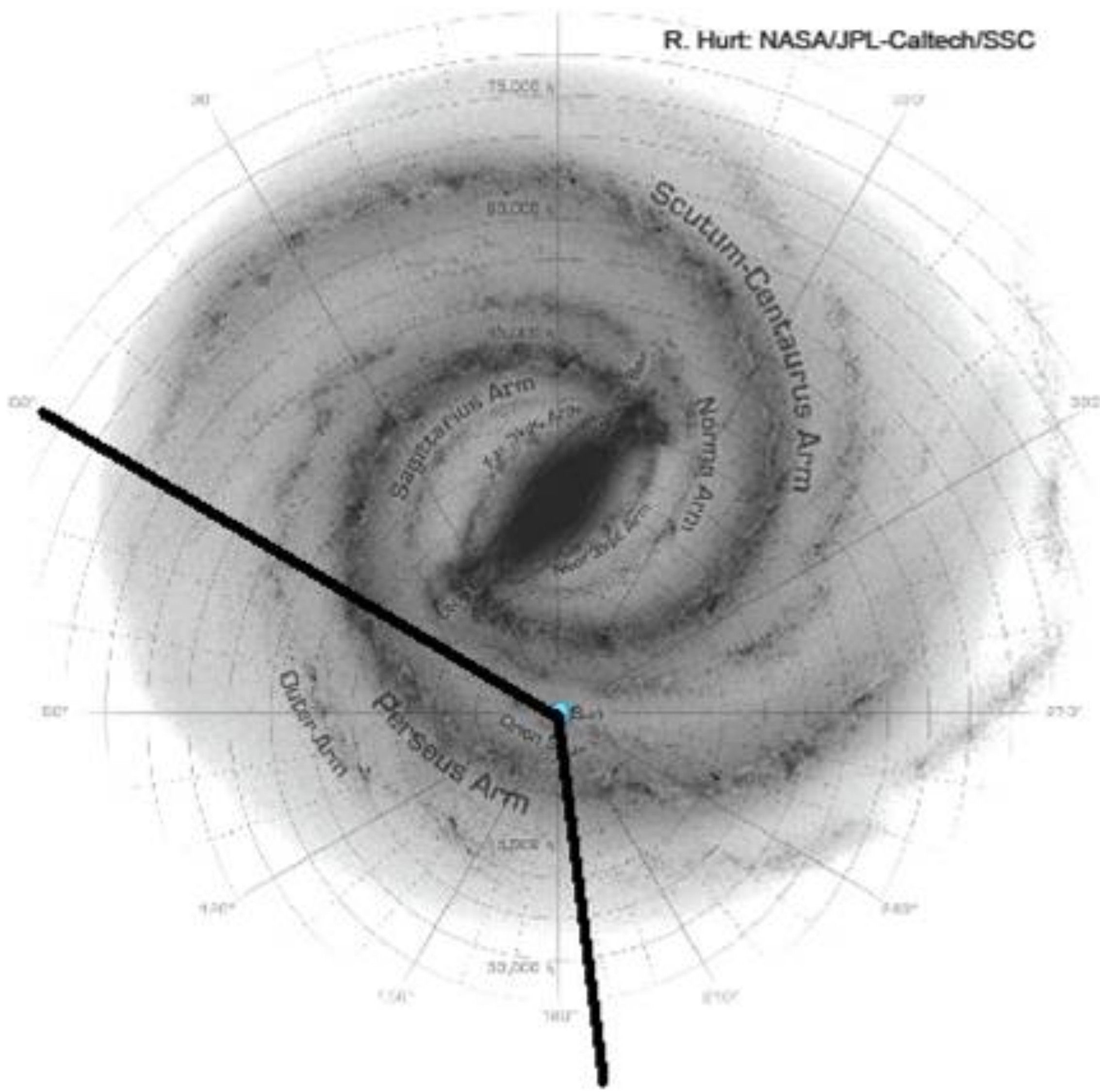
Our Galaxy is thought to be a spiral Galaxy, and we are all aware that the details are very uncertain, because mapping it from within is very difficult



R. Hurt: NASA/JPL-Caltech/SSC
Scutum-Centaurus Arm
Sagittarius Arm
Norma Arm
Perseus Arm
Outer Arm



(2')
Carina
(1')
Crux
Sagitt.
(1)
Norma
Scutum
3-kpc
(2)


R. Hurt: NASA/JPL-Caltech/SSC
Scutum-Centaurus Arm
Sagittarius Arm
Norma Arm
Outer Arm
Perseus Arm

- Remember – these limits for the Parkes telescope are well above the horizon – at an elevation above 30 degrees – all good observations!

- So Parkes can make a unique impact on the study of Galactic structure.

- And of course, the Parkes suite of excellent receivers complement its location.

The Parkes HI interferometer

- Pioneered by Radhakrishnan in the late 1960s to study cold HI.
- But contributions to distance determinations were of great value and deserved further study
- Continuation with John Murray, Dave Cooke and Doug Cole, and Rob Roger visiting from Penticton.

Astron. & Astrophys. 45, 239–258 (1975)

Neutral Hydrogen Absorption Measurements Yielding Kinematic Distances for 42 Continuum Sources in the Galactic Plane*

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Received April 15, 1975

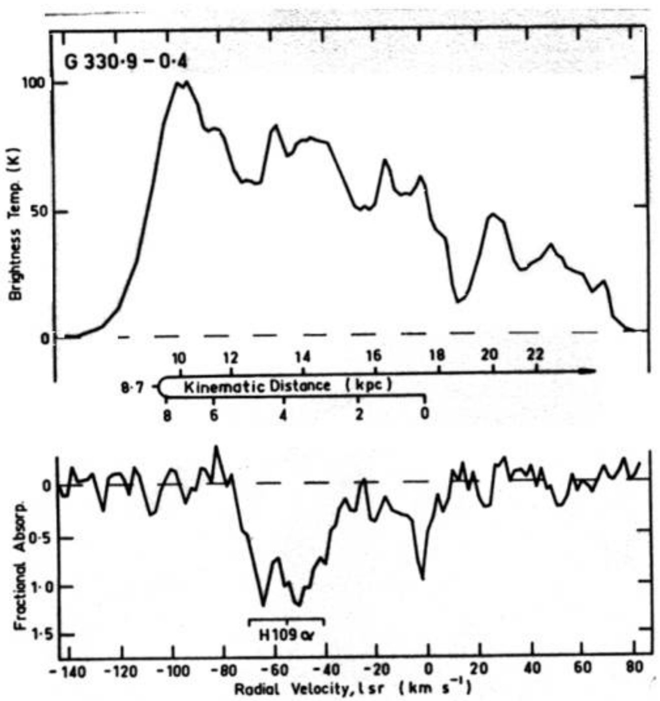
Summary. The Parkes hydrogen line interferometer has been used to measure 21 cm absorption profiles for 42 radio sources: approximately half are supernova remnants and most of the remainder are H II regions. We have used the results to determine kinematic distances to the sources and have thus greatly increased the number of galactic radio sources with well-determined distances. For supernova remnants this is of special importance, since very few reliable distance calibrators have previously been available.

Key words: H I absorption — kinematic distances — H II regions — supernova remnants

1. Introduction

The problem of measuring reliable H I absorption spectra for sources at low galactic latitudes has been extensively discussed by Radhakrishnan *et al.* (1972a), who conclude that where very small beam sizes are not available the most satisfactory solution lies in the use of an interferometer. This allows the "reference profile" in order to establish a more reliable distance scale for these objects, and (b) H II regions, especially those with associated OH or those of particularly high emission measure.

Maps of the continuum brightness distribution made with beam sizes of 3′ or 4′ have been published for most



Galactic structure

- Initially using the known HII regions and supernova remnants studied with the Parkes interferometer – but then requiring a huge new survey – the 5-GHz Galactic Plane survey with Raymond Haynes. Predominantly recognising HII regions which could then be studied for recombination line emission, and hence kinematic distances.
- Leading to an early version of spiral structure.

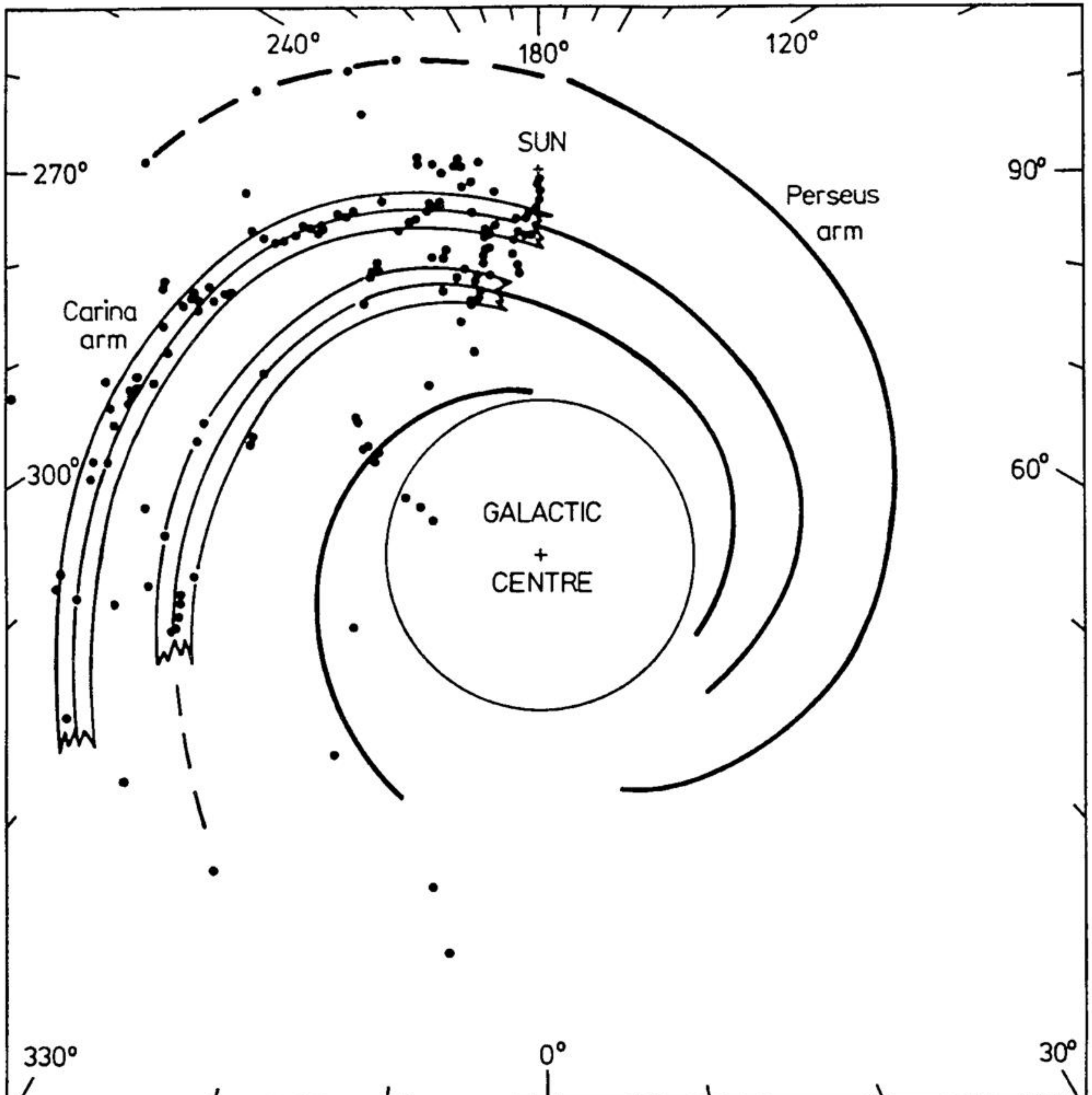


Fig. 5. Spiral pattern delineated by H II regions in the Galaxy. Individual H II regions from the present work are shown only if there is no distance ambiguity. Two segments of spiral arms derived from the present work are shown with thickness 1 kpc. The single-line spiral pattern is from Georgelin and Georgelin (1976), modified by Downes et al. (1980); the broken line extension of the Perseus arm is suggested by the present data

- ***1967: my first acquaintance with masers etc.***
- ***1970: first acquaintance with Parkes***
- ***1971?: first Parkes data at 22 GHz***
- ***1972: HI with the Parkes interferometer***
- ***1973-1982: the Parkes OH surveys***
- ***1987-1993: methanol at Parkes***
- ***1998-2001: OH maser VLBI***
- ***2003: Methanol Multibeam survey***

OH masers, the 1970s

- Initially with Brian Robinson and Miller Goss, and with state of the art parametric amplifiers from Mal Sinclair.
- 'Surveys' firstly needed to discover a large enough sample to explore the variety of masers existing in our Galaxy.
- Would they be useful for Galactic studies?

Water masers

- Water masers with Ken Johnston, Brian Robinson, Bob Batchelor. Above 20 GHz, this was a new challenge for Parkes.

- The discovery that both red and blue-shifted emission was common. Some especially puzzling ones, recognised as strong outflows
- Providing clear evidence of energetic outflows occurring during massive star formation

The problem of positions

- No suitable southern interferometer prior to AT Compact Array. So we used the VLA as far south as physically possible – working with Rick Forster studying both OH and water masers, and verifying their close association.

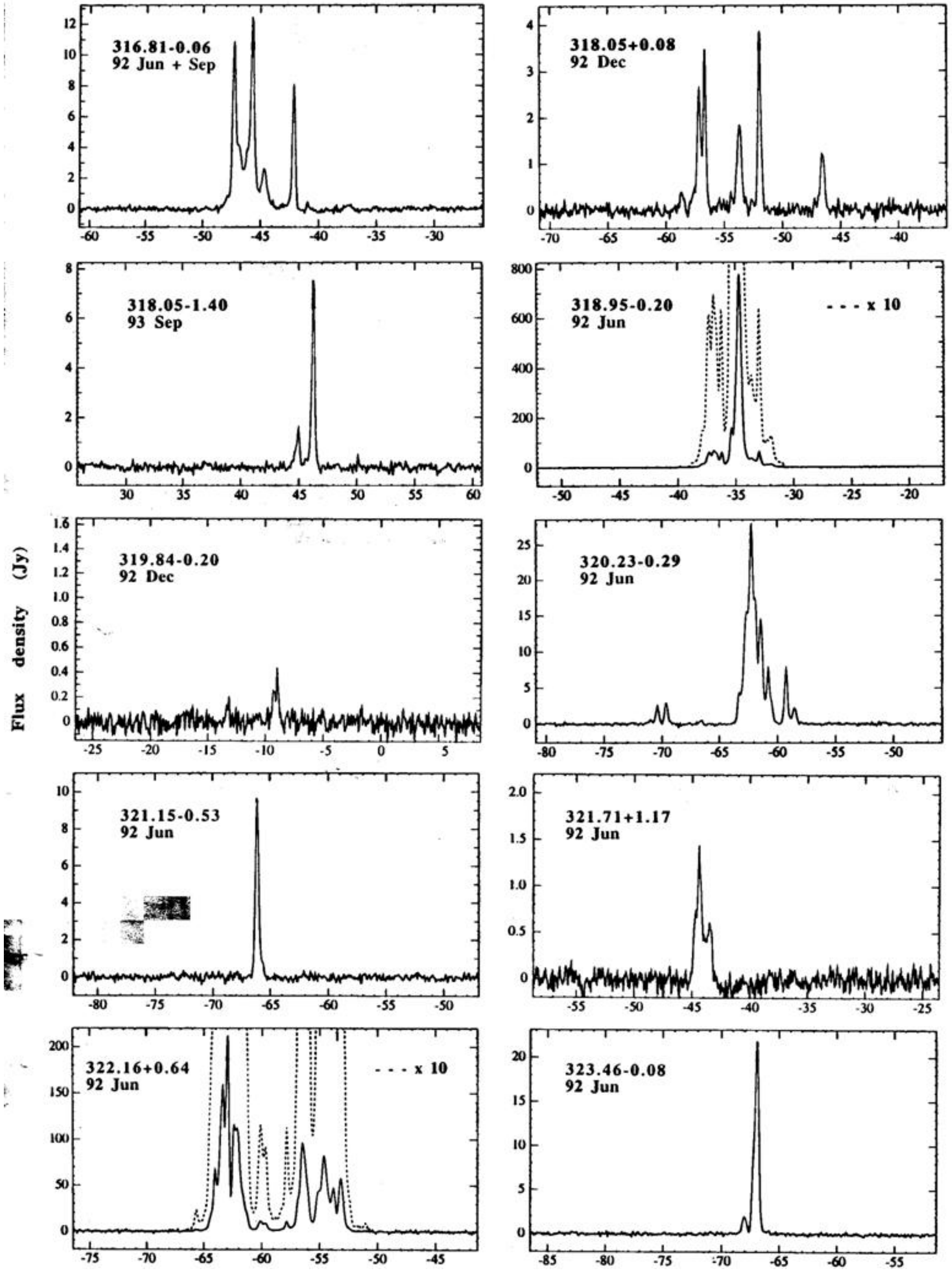
Parkes and the ATCA

Once the ATCA came into operation (1988), their co-existence yielded an incredibly productive combination.

It was possible to use the high spatial resolution of the ATCA for accurate positions, and Parkes, with its superior spectroscopic performance, for the high velocity resolution polarimetry.

The methanol 'explosion'

- In swift succession, the masing transitions of methanol at 12.2 and 6.6 GHz were discovered to surpass even OH and water in their usefulness for pinpointing new sites of massive star formation.
- Southern studies of OH and water were almost suspended to assess the methanol maser population, using Parkes searches at the sites of the OH and water masers.


316.81-0.06
92 Jun + Sep
318.05+0.08
92 Dec
318.05-1.40
93 Sep
318.95-0.20
92 Jun
- - - x 10
319.84-0.20
92 Dec
320.23-0.29
92 Jun
321.15-0.53
92 Jun
321.71+1.17
92 Jun
322.16+0.64
92 Jun
- - - x 10
323.46-0.08
92 Jun
Flux density (Jy)

The purpose of surveys

- Depends on previous knowledge and the space density of the expected population.
- If very few objects known, main purpose may simply be to expand the sample

- **If low space density, much of the importance of a uniformly sensitive large survey is to define the regions where there is nothing!**
- **In a few cases, eg a finite Galactic population, we may discover the whole population!**

A new project-the MMB survey

- A Galactic plane unbiased methanol survey (planned 2003) at 6.6 GHz – Parkes or ATCA?
- Parkes preferred because the ATCA was awaiting receiver upgrade at 6.6 GHz (we still wait…….), and the new ATCA spectrometer (CABB) was also not yet operational.
- MMB now complete: Jimi Green will discuss details and its exciting outcomes. However it is especially appropriate to mention it here:

2. Parkes 64m Telescope

2.1. 6GHz focal plane array

Project Leader: M. Sinclair, Project Scientist: J.L. Caswell
Proposed: 2001 Feb 1 Funding: not_funded

A Multi-beam system with 7 feed horns, covering the frequency range 6.0 to 6.7 GHz is proposed. This is a potential joint project with Jodrell Bank Observatory.

The prime scientific objective would be a sensitive unbiased survey of the Galactic plane for masers at the 6.6-GHz transition of methanol. At Parkes, the spectrometer would be the existing MultiBeam correlator, concatenated to give 2048 channels for each polarization on each of the 7 beams. A survey taking several months at both Jodrell Bank and Parkes could cover the full Galactic plane with latitude coverage +/- 2 degrees, with a detection limit better than 1 Jy (5-sigma). Such an unbiased survey could expect to at least double the number of known methanol masers to more than 1000, and deeper surveys could be envisaged where appropriate. The detected masers would provide a definitive census of regions with ongoing massive star formation throughout the Galaxy, and these in turn would be superb targets for follow up at both mm-wavelengths and the IR (initially with existing facilities such as Mopra, SEST, the upgraded ATCA, and subsequently with ALMA, SOFIA, and space IR missions).

Timescale: the Jodrell observations await the upgrade of the Lovell telescope, available 2003; ATNF resources are currently focused on completion of mm-receiver installation on the ATCA. Compatibility of 6-GHz MB feed and receiver requirements at Jodrell and Parkes are being explored, and will dictate the degree of cost sharing possible.

For comparison with the HI MB system, note that this is a much smaller receiver package (at less than one-quarter of the wavelength, and with only 7 beams rather than 13). System parameters are excellent for several other projects: the lower end of the frequency range encompasses transitions of excited OH that are often prominent masers in Star Forming Regions. Pulsars tend to be weak at this quite high frequency, but the reduced scattering will make the receiver of special value for some pulsar observations.


National Radio
Astronomy
Observatory
Very
Large
Array

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. 404, 1029–1060 (2010) doi:10.1111/j.1365-2966.2010.16339.x

The 6-GHz methanol multibeam maser catalogue – I. Galactic Centre region, longitudes 345° to 6°

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ABSTRACT

We have conducted a Galactic plane survey of
beam receiver on the Parkes telescope. Here
provides sensitive unbiased coverage of a large
given for 183 methanol maser sites in the longi
6°. Within 6° of the Galactic Centre, we foun
are new discoveries. The masers are confined
of many sources at the Galactic Centre dista
population; there is no high-latitude populatio

Within 2° of the Galactic Centre the maser
a range much smaller than the 540 km s^{-1} ran
highest positive velocity (+107 km s^{-1}) occurs
ably attributable to the Galactic bar. The maser
is near longitude 346°, within the longitude–ve
It has the most extreme velocity of a clear pop
far sides of the 3-kpc arm. Closer to the Galac
low, except within 0.25 kpc of the Galactic C
it is 50 times higher, which is hinted at by th
unusual velocities.

Key words: masers – surveys – stars: formati

1 INTROD

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†Deceased 2006 November 1.

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The 6-GHz methanol multibeam maser catalogue – II. Galactic longitudes 6° to 20°

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ABSTRACT

We present the second portion of an unbiased
methanol masers. This section of the survey sp
the detection of 119 maser sources, of which 4
constrained to the Galactic plane, with only four
region includes the brightest known 6668-MHz
two brightest newly discovered sources in the
sources associated with the 3-kpc arms within ±
beyond 15° longitude. We identify three new
comment on the density of masers in relation to

Key words: masers – surveys – stars: formati

1 INTRODUCTION

The Methanol Multibeam (MMB) survey is a project to survey the entire Galactic plane for 6668-MHz methanol masers (Green et al. 2009a). This species of maser is one of the brightest observed; it is widespread throughout the Galaxy, and it exclusively traces high-mass stars in an early stage of their formation (Pestalozzi, Humphreys & Booth 2002; Minier et al. 2003; Xu et al. 2008). This makes the 6668-MHz methanol maser a powerful tool for understanding the processes of high-mass star formation and studying the spiral arm structure of our Galaxy (e.g. Reid et al. 2009; Rygl et al. 2010). By surveying in an unbiased manner, with uniform sensitivity, the MMB will establish a definitive catalogue for future studies. More than 60 per cent of the Galactic plane has now been observed with the Parkes Radio Telescope and detections followed up to yield accurate positions (≤0.4 arcsec). The catalogue is being released sequentially, as data reduction and follow-up observations are completed. The first region to be released covered Galactic longitudes 345° to 6° (Caswell et al. 2010), with a focus on recognizing masers associated with the Galactic Centre. The current paper extends the Galactic Centre region to a longitude of 20°, and represents the remaining sources north of the Galactic Centre which have high-resolution positions from the Australia Telescope Compact Array (ATCA). For sources further north we are obtaining positions with

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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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The 6-GHz methanol multibeam maser catalogue – III. Galactic longitudes 330° to 345°

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ABSTRACT

We present results from the third portion of the Methanol Multibeam Galactic plane survey of masers at 6668 MHz. It covers the longitude range 330°–345°, yielding 198 masers, of which more than 40 per cent are new discoveries. The maser population in this longitude range is the densest anywhere in the Galaxy, with many sources delineating a large portion of the Norma spiral arm close to its tangent point, and a cluster defining the southern tangent point of the 3-kpc ring. Two sources lie outside the solar circle, on the far side of the Galaxy, more than 15 kpc away.

Key words: masers – surveys – stars: formation – ISM: molecules – Galaxy: structure.

1 INTRODUCTION

Methanol masers at 6668 MHz are tracers of massive young stars and provide an unrivalled means of mapping massive star formation throughout our Galaxy since they are bright and unaffected by foreground absorption. The Methanol Multibeam (MMB) project is a sensitive survey for these masers throughout the Galactic disc which will provide a definitive catalogue for Galactic studies. The survey description (Green et al. 2009) and two major portions of the catalogue have been released (Caswell et al. 2010a; Green et al. 2010) and here we present the third portion surveying Galactic longitudes 330° to 345°, a region containing the densest concentrations of masers in the whole Galaxy. Previous unbiased surveys have been made of longitudes 330.°8 to 339.°8 very close to the plane (Caswell 1996), and 325° to 335° for a larger latitude range (Ellingsen et al.

2 THE METHANOL MULTIBEAM SURVEY EQUIPMENT AND PARAMETERS

The detailed plans and strategy of the MMB survey have been described fully by Green et al. (2009). Here we merely recall the essential parameters.

The Galactic latitude coverage is $|b| \leq 2°$ and the velocity coverage is at least 180 km s^{-1}, but adjusted so as to include the velocity range of all known Galactic CO emission (Dame, Hartmann & Thaddeus 2001). Between 330° and 340°, central velocity settings were varied from −50 to −70 km s^{-1}, and coverage was increased for regions 340° to 345° by overlapping settings centred at −145 and 0 km s^{-1}. Initial survey observations at Parkes for this section were completed between 2006 January and 2007 June. The rms noise sensitivity of the basic survey at Parkes is 0.17 Jy, but more

A few diversions

- I have indicated the very non-linear path in our study of the Galaxy – zigzagging with priorities as unexpected discoveries arose.
- and zigzagging with instruments as we used Parkes, its interferometer, the VLA, the AT Compact array and the AT Long Baseline Array.

The LBA

- For spectroscopic mapping of masers, despite its ad hoc nature, the LBA, even in 3-element form, is excellent.
- It is a worthy southern counterpart to MERLIN, with comparable capability.

- Some examples:

OH300.969 Magnetic Fields

Ring shape distribution

Ordered B - field strength

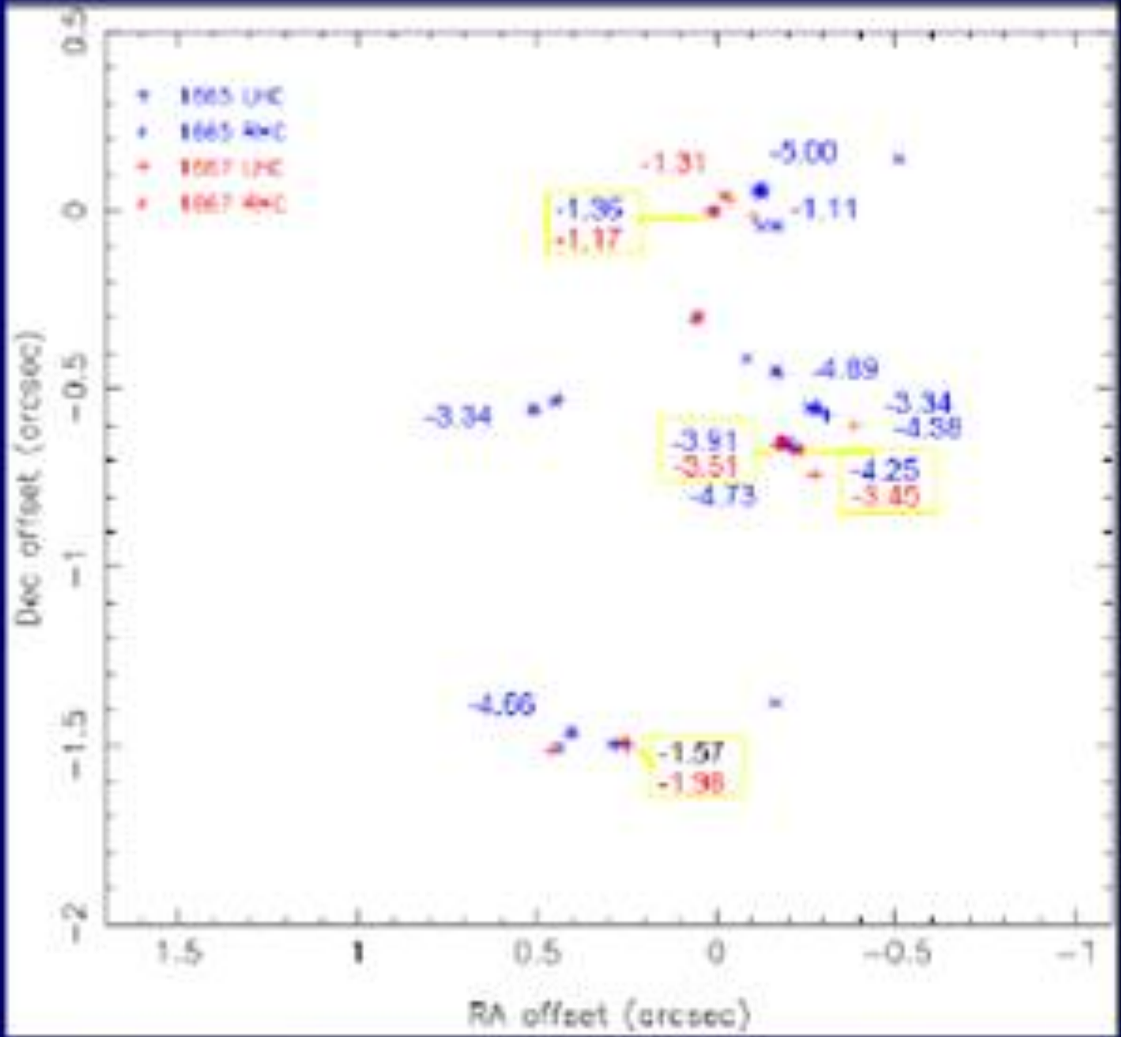
~ 1 – 5 mG

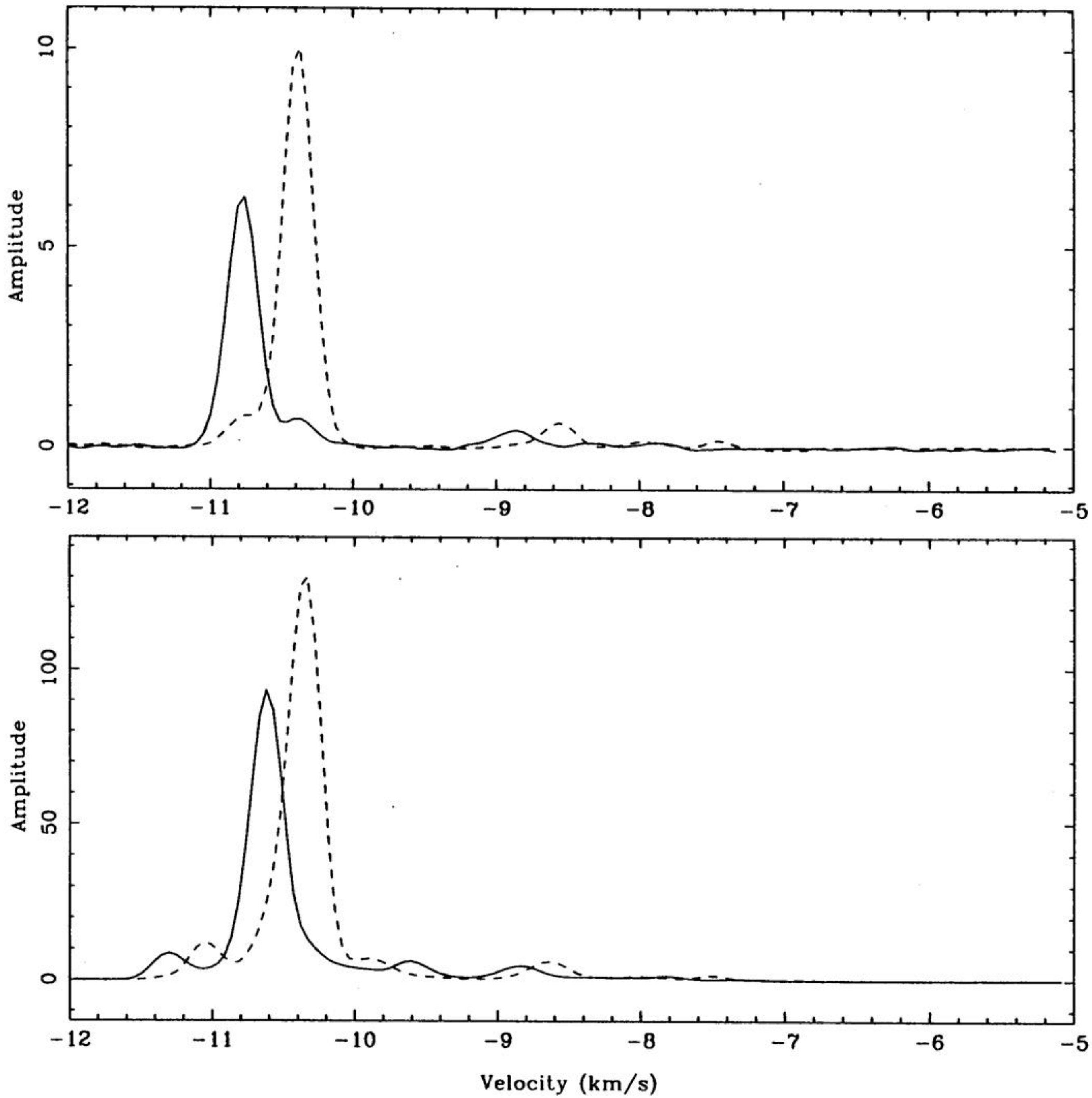
No field reversal found

Both 1665 and 1667 at

the same places – give

similar field strengths





Amplitude
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−7
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−5
Amplitude
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50
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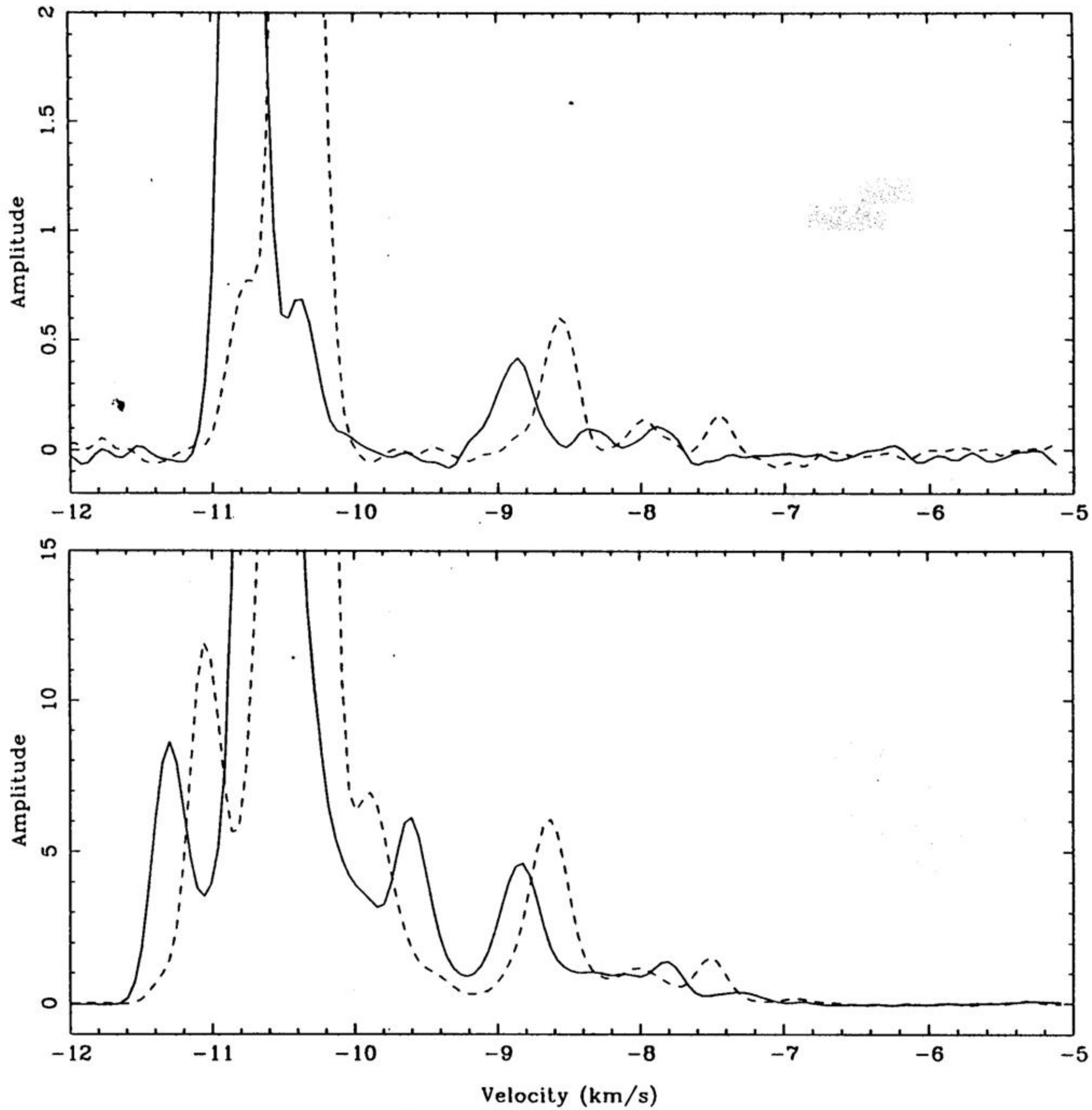
−12
−11
−10
−9
−8
−7
−6
−5
Velocity (km/s)



2
1.5
1
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0
Amplitude
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-10
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-8
-7
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-5
15
10
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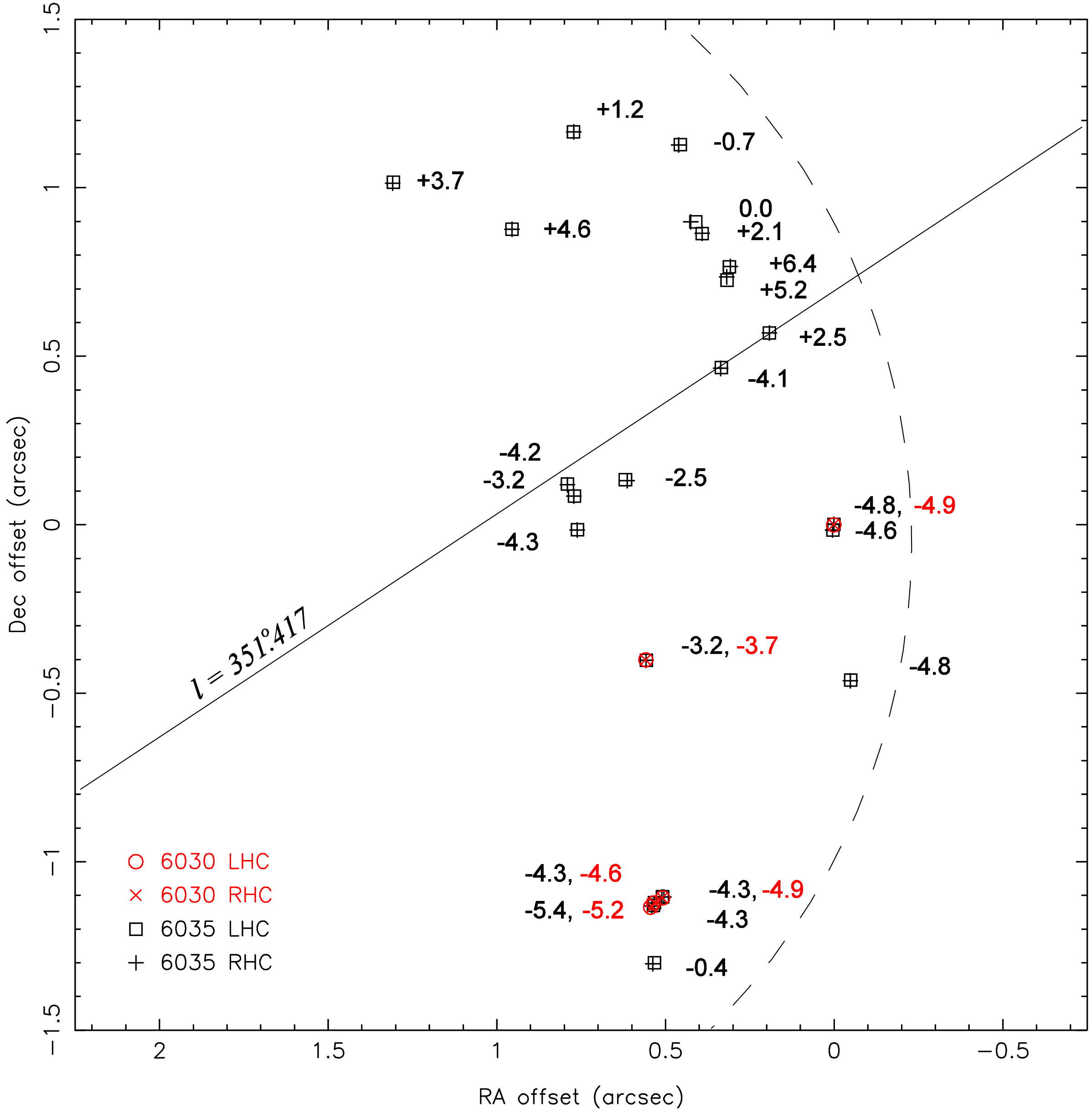
Amplitude
-12
-11
-10
-9
-8
-7
-6
-5
Velocity (km/s)



Dec offset (arcsec)
RA offset (arcsec)
1.5
1
0.5
0
−0.5
−1
−1.5
2
1.5
1
0.5
0
−0.5
$l = 351°.417$
+1.2
-0.7
+3.7
+4.6
0.0
+2.1
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-4.2
-3.2
-2.5
-4.3
-4.8, -4.9
-4.6
-3.2, -3.7
-4.8
-4.3, -4.6
-5.4, -5.2
-4.3, -4.9
-4.3
-0.4
6030 LHC
6030 RHC
6035 LHC
6035 RHC

The future: 1

The (spiral) structure and velocity field of the Galaxy

- The objective: LBA maser astrometry with precision to measure parallaxes, hence precise geometric distances, over the whole Galaxy.
- A project begun already, with demonstration that methanol masers at 6.6 GHz (using EVN), 12 GHz (using VLBA), and water masers at 22 GHz (using VERA) can all be used.
- The southern sky will greatly benefit from the sensitive large Parkes dish as an element of the LBA at both 6.6 GHz and at 22 GHz.

The Distance to the Perseus Spiral Arm in the Milky Way

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We have measured the distance to the massive star–forming region W3OH in the Perseus spiral arm of the Milky Way to be 1.95 ± 0.04 kiloparsecs (5.86×10^{16} km). This distance was determined by triangulation, with Earth's orbit as one segment of a triangle, using the Very Long Baseline Array. This resolves the long-standing problem that there is a discrepancy of a factor of 2 between different techniques used to determine distances. The reason for the discrepancy is that this portion of the Perseus arm has anomalous motions. The orientation of the anomalous motion agrees with spiral density-wave theory, but the magnitude of the motion is somewhat larger than most models predict.

Massive stars and their associated bright regions of ionized hydrogen trace the spiral arms of galaxies. However, for our galaxy, the Milky Way, our view from the interior makes it difficult to determine its spiral structure. In principle, one can construct a simple model of the rotation speed of stars and gas as a function of distance from the center of the Milky Way. Then, if one measures the line-of-sight component of the velocity of a star or interstellar gas, one can determine its distance by matching the observation with the model prediction (that is, a kinematic distance). Knowing the distances to star-forming regions, one can then locate them in three dimensions and construct a "plan view"—a view from above the plane—of the Milky Way. Unfortunately, many problems arise when constructing a plan view of the Milky Way, including (i) difficulties in determining an accurate rotation model (which requires values for the distance and orbital speed of the Sun from the center of the Milky Way), (ii) distance ambiguities in some portions of the Milky Way (where an observed velocity can occur at two distances), and (iii) departures from circular rotation (as might be expected for spiral structure). Progress has been made on the first two problems. For example, many kinematic distance ambiguities can be resolved by interferometric studies of hydrogen absorption at radio frequencies, because distant sources will show a greater velocity range for hydrogen absorption than will near sources (*1*). However, the third problem, noncircular motions, is fundamentally much harder to address.

The Perseus arm is the nearest spiral arm outward from the Sun (Fig. 1) (*2*, *3*). There are many star-forming regions in the Perseus arm for which distances have been estimated from the difference between the observed and intrinsic luminosities of massive young (O-type) stars. Toward Galactic longitudes from 132° to 138°, such luminosity distance estimates are ≈2.2 kiloparsecs (kpc) (*4*). However, kinematic distance estimates for these regions are much greater. Stars and gas in this region of the Perseus arm are observed to move with line-of-sight velocities of about -45 km s^{-1}, relative to the local standard of rest (LSR) (*5*). Assuming that the Milky Way rotates at 220 km s^{-1}, independent of the distance from its center, and that the Sun is at a distance of 8.5 kpc from the center (*6*), the observed Perseus arm velocities occur at distances of >4 kpc. The discrepancy between distances based on stellar luminosities and velocities has never been resolved.

The problem of determining the distance to the Perseus arm can be resolved by determining an accurate distance to a massive star–forming region in the arm. The best and most reliable method for measuring distance in astronomy is called a trigonometric parallax. A trigonometric parallax is determined by observing the change in position of a star, relative to very distant objects such as quasars, as Earth moves in its orbit about the Sun. The parallax is simply the maximum angular deviation of the apparent position from its average position over a year. The deviation in position of a source over a year is very small. For example, the parallax for a source at a distance of 2 kpc, or about one-quarter of the distance to the center of the Milky Way, is only 0.5 milli–arc second (mas).

The distance D to a source is easily calculated from its parallax π by triangulation: $D(\text{kpc}) = 1/\pi(\text{mas})$. Thus, one needs a measurement accuracy of 0.05 mas to achieve 10% accuracy for a source at 2 kpc distance, which would be sufficient to resolve the Perseus arm discrepancy. By comparison, trigonometric parallaxes obtained by the Hipparcos satellite (*7*) typically have uncertainties of only ≈1 mas, which is inadequate for our purposes.

An ideal candidate for a trigonometric parallax measurement is the massive star–forming region W3OH, located at Galactic longitude 134° and near O-type star associations. W3OH has strong methanol masers (*8*, *9*), which can serve as bright, relatively stable beacons for astrometric observations at radio wavelengths. In this paper, we describe observations with the Very Long Baseline Array (VLBA), consisting of 10 radio telescopes spanning Earth from Hawaii to New England to the Virgin Islands and operated by the National Radio Astronomy Observatory (*10*), which allowed us to achieve an extraordinarily accurate (0.01-mas) paral-

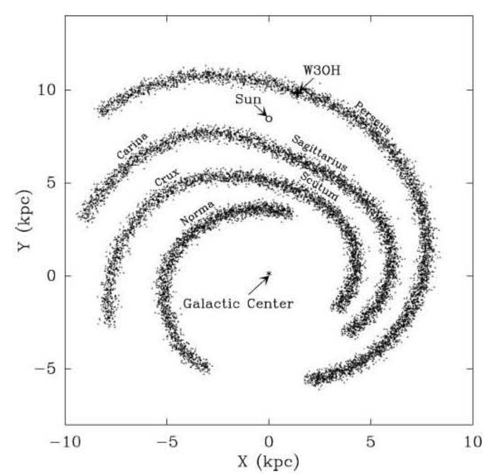

Fig. 1. Plan view of the Milky Way as seen from its north pole. Estimated locations of spiral arms (*2*, *3*) are indicated by the large number of dots and labeled by a prominent constellation onto which they are projected. The locations of the Galactic Center, Sun, and W3OH are indicated.

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The future: 2
The magnetic field of our Galaxy

- Using OH masers to map the magnetic field over the whole Galaxy.
- Initially Parkes spectro-polarimetry, and now with the ATCA and CABB

CONCLUDING REMARKS II

RADIO OBSERVATIONS

Gart Westerhout
University of Maryland

I came to this conference thinking I didn't know very much about HII regions. I think the conference has been extremely successful because now I don't understand HII regions at all.

In the case of OH (paraphrasing from von Hoerner and Solomon) we now have three groups of theories: those we know are wrong, those of which we don't know yet that they are wrong, and those we haven't invented yet. The one conclusion I arrived at from hearing the various theories is that both the long base line and the short base line interferometer observations should be repeated many times. On the very small scale we are talking about, the objects could be expected to move in relatively short periods of time, which might well lead to some very interesting conclusions. I want to ask one question here: how relevant are the OH observations to astrophysics, to our understanding of the total behavior of the interstellar medium? Could it be that the emission is a pointer to regions of incipient star formation? Personally I would say that the OH 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.