Summary of the "Sub-microJansky Radio Sky" workshop

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Abstract

The Square Kilometre Array Radio Telescope is the next generation radio telescope. An international project is currently underway to design and build an instrument having an effective collecting area two orders of magnitude greater than any existing telescope. A number of separate studies are presently investigating how to design the Square Kilometre Array to best carry out the kinds of observations desired by the astronomical community. We present a summary of one of these studies, a workshop called the "Sub-microJansky Radio Sky," held at ATNF, Sydney, on 17 June 1998. This workshop addressed the nature of the radio sky at the very faint flux densities likely to be attainable by the Square Kilometre Array. In particular, each speaker investigated a separate population of radio sources and how the expected appearance of that population at such faint flux densities would dictate how to refine some of the design constraints for the Square Kilometre Array.

Keywords:
Cosmology: early universe — instrumentation: interferometers — methods: observational — radio continuum: general — telescopes

1 Introduction

It is well established that most scientific advances follow technical innovation (e.g. Harwit 1981). De Solla Price (1963) reached the same conclusion from his application of quantitative measurement to the progress of science. His analysis also showed that the normal mode of growth of science is exponential. A plot of the sensitivity of telescopes used for radioastronomy since the discovery of extra-terrestrial radio emission in 1940 shows this exponential character (Figure 1) with an increase in sensitivity of 10^5 since 1940, doubling every 3 years. To maintain the extraordinary momentum of discovery of the last few decades a very large new radio telescope will be needed.

An increase in sensitivity of this order cannot be achieved by improving the electronics of receiver systems, but only by *increasing the total effective collecting area of radio telescopes to about a million square metres.* The project has therefore acquired the appellation, the Square Kilometre Array. The time frame during which a new radio facility is needed to complement other planned instruments will be in the years around 2010.

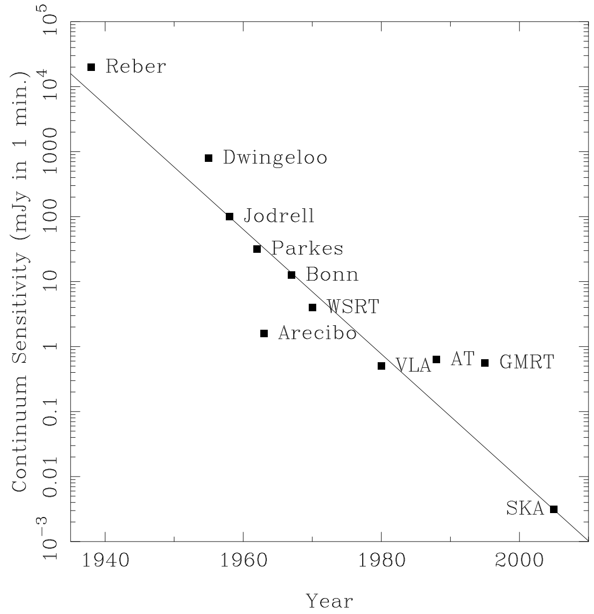

Figure 1: Radio telescope sensitivity as a function of time.

2 The Square Kilometre Array project

Under the auspices of the Large Telescope Working Group (LTWG), established in 1993 by the International Union of Radio Science (URSI), a large scientific community is now cooperating to discuss the technical research required for the realisation of the project. A group of 6 countries (Netherlands, U.S., China, Canada, Australia and India) are at present actively working on the technology study program. An internet site (`http://www.atnf.csiro.au/1kT/`) provides up-to-date information about the project (including the latest news, scientific and technical documents and the list of participant institutes).

At an earlier workshop (held in Sydney in December 1997), a list of preliminary specifications for the Square Kilometre Array was compiled (see `http://www.atnf.csiro.au/1kT/`, or `http://www.nfra.nl/skai/science/index.htm`). These specifications make it clear that the Square Kilometre Array will be the world's premier astronomical imaging instrument. It will have a spatial resolution better than the Hubble Space Telescope (< 0.1 arcsec), a large field of view (~ 1 square degree), a spectral coverage of more than 50% ($\nu/\Delta\nu < 2$), a spectral resolution sufficient for kinematic studies ($\nu/d\nu > 10^4$), and all at a sensitivity which is about 100 times that which is now available.

By comparison, the largest optical integral field units which are now being considered for construction on 8 m telescopes would only provide a field of view of perhaps 1 arcmin on a side with 10% spectral coverage at a comparable resolution, while the next generation of millimetre arrays is envisaged to provide a field of about 40 arcsec with perhaps 10% spectral resolution.

There are still many possible hardware designs for the Square Kilometre Array, and a lot of effort is being devoted to ongoing studies to establish how each will address the desired specifications. The scientific justification for such an instrument is reaching maturity. The latest international meeting (held during July 1998 in Calgary) was devoted to producing the formal science case for the Square Kilometre Array. This will be used to refine the technical specification and design studies for the instrument.

In preparation for the Calgary meeting a workshop was held in June in Sydney, where Australian astronomers could speculate on the nature of the sub-microJansky radio sky and provide their own list of desired specifications for the Square Kilometre Array. This workshop investigated some specific areas of interest but did not cover all possible science goals which might be addressed with the Square Kilometre Array. However, with the advent of a new technology it is often not the questions expected to be answered which provide the most important discoveries, but those which no-one had thought to ask.

Perhaps the most exciting science driver for the Square Kilometre Array is the opportunity to study the origins of star- and galaxy-formation in the Universe, along with the large scale structure which is intimately connected with this process. This will be done through observations of redshifted HI and non-thermal emission from star forming regions in normal galaxies, like our own, at cosmological distances. However, the specifications for an instrument which can make such observations also allows the study of a wide range of other scientific targets. Amongst these are radio stars, pulsars, extended structures within the Milky Way, radio emission from normal galaxies, masers and spectral line studies, all of which were discussed in this workshop. There are many other astrophysical questions which the Square Kilometre Array will also address which were not discussed (e.g. galaxy evolution, large scale structure, gravitational lensing, Sunyaev-Zeldovich clusters, gamma ray bursters, extra-solar planets, solar-system objects, SETI applications, etc.) and the reader is directed to the most recent draft science case (LTWG 1998) for more information. Most of the material discussed during this workshop echoes aspects of material also developed by the LTWG, which will be available in full detail in the formal science case now being developed.

To provide a taste of the science which will be possible with the next generation radio telescope, and to list some of the instrumental specifications required along with some of the problems to be addressed, the topics discussed in the "Sub-microJansky Radio Sky" workshop are presented here.

3 Primordial HI – Lister Staveley-Smith

The schematic diagram shown in Figure 2 gives an outline history of the universe as it is currently understood. In typical Cold Dark Matter (CDM) cosmologies the first objects form some time between $z \approx 10$ and 30. This implies there must be sources of ionizing radiation at early epochs so far not observed directly, and these sources must have been sufficiently abundant to reionise the Universe fully by $z \approx 5$. The temperature of the primordial HI will be raised above the radiation temperature through adiabatic compression of overdense regions well before reionisation, however, and hence the medium surrounding primordial objects, even before the first galaxies have formed, will show emission in the 21 cm line. This emission is expected to be directly observable with the Square Kilometre Array. Apart from allowing us to detect objects at unprecedented redshifts, observations of this emission will provide vital information about the processes responsible for the reionisation. Important questions able to be addressed by HI observations include:

- When did the first stars form? At some redshift beyond 10 in a CDM Universe objects will start to form which are sufficiently massive to lead to the production of primordial star clusters.

- What is the redshift of reionisation? The process of reionisation also probes the $10^6 - 10^9\ M_\odot$ range, allowing discrimination between competing CDM cosmological models which predict fluctuations on such scales.

- Where is the peak in star-formation for more recent galaxies ($z \approx 1 - 3$)?

- When and how do gaseous disks collapse?

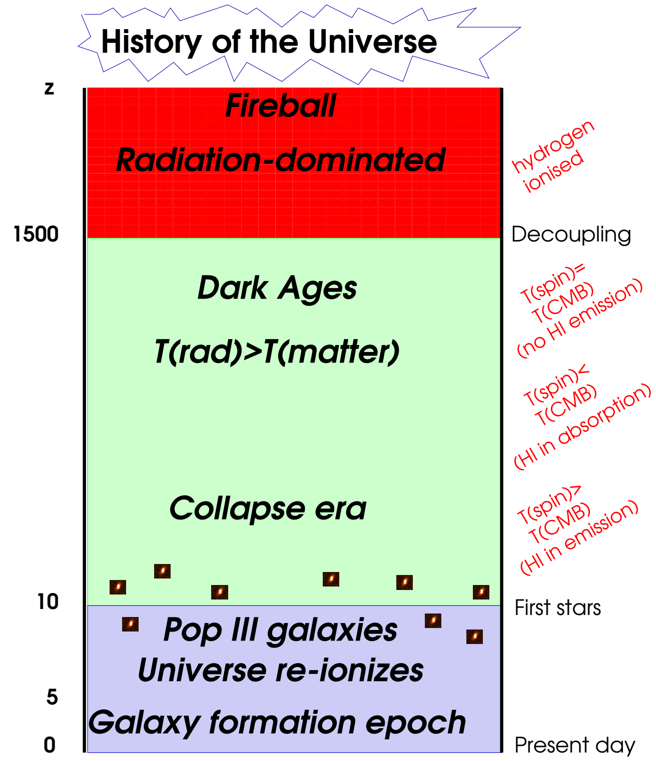

Figure 2: A schematic history of the universe, showing the approximate redshifts at which various events are believed to occur.

- What is the relationship between gaseous disks and damped Lyα systems?
- How does the Tully-Fisher relationship evolve with redshift?

The primordial universe and the more recent, or 'normal,' universe both offer insights into aspects of these questions. However the telescope specifications for making such observations are highly dependent on the redshift of interest, and are shown in Table 1. In some senses, an instrument designed solely to investigate the very high redshift universe would have specifications easier to meet than one designed to investigate more recent redshifts.

Table 1: Telescope requirements.

	Primordial $z \approx 10$	Normal $z \approx 3$
Frequency	130 MHz	350–1420 MHz
Resolution	1 kHz	400 Hz
Bandwidth	70 MHz	300 MHz
Channels/Baseline	10^5	10^6
Angular resolution	$2'$	$0''.3$
Longest baseline	4 km	600 km
Sensitivity	1 μJy	0.5 μJy

3.1 Potential problems

There are many anticipated problems deriving from various sources of interference, and this subject has been addressed to a greater or lesser extent elsewhere with various proposed strategies for minimisation of the effects. Just to emphasise the importance of the problem, however, 1 μJy is a 100 kW VHF TV transmitter at 6000 AU. Confusion is also a major problem. At 130 MHz, if the confusion level is $\approx$1 Jy and the rms is $\approx 1\,\mu$Jy, then a continuum suppression of 10^6 is required. Although the Australia Telescope Comact Array (ATCA) is capable of achieving spectral dynamic ranges of almost 10^4, these are not easily achievable through ordinary techniques. So this area will need a lot of effort if a low resolution array requires this to be bettered by more than two orders of magnitude. Aspects of the confusion problem also imply limitations for the field of view. A wider field of view implies worse confusion. Assuming 4 hours per field, to map the *whole sky* in ten years only needs a field of view of $\approx$1 degree. This in turn implies a maximum element size of $\approx$130 m. Another recognised problem is the large number (up to 10^{12}) of correlators per beam required. (c.f. 3×10^4 for the Parkes multibeam). There may also be problems obtaining the anticipated resolution of the Square Kilometre Array. Even a resolution of $0\farcs3$ may be difficult due to problems with scintillation and the ionosphere. Additionally, the receiver temperature, $T_{\rm sys}$, needs to be cooler than 50 K (excluding background).

4 Galaxy source density – Andrew Hopkins

At bright flux densities radio galaxies are dominated by sources with high radio luminosity and the traditional double-lobed morphology of the FRI and FRII classes. However, as objects with ever fainter radio flux densities are observed the dominant population changes to one whose radio emission is derived, not from ultra-relativistic jets, but from extremely high rates of star-formation (Condon 1989; Benn et al. 1993). This new population of starburst galaxies starts becoming dominant at flux densities of a few mJy. As flux density continues to decrease, more distant starburst populations will become evident, as will less vigorous local starbursts, until, it is assumed, the measurements of radio emission are sensitive enough to detect the star-forming processes in "normal" galaxies.

As an element in a Square Kilometre Array design study, a model to simulate the radio sky down to arbitrarily faint flux densities is useful for a number of reasons. One of the main ones, perhaps, is that a simulation of the radio sky can be applied to model telescope designs to distinguish the optimum solution. However, there is also the opportunity to provide models for a range of different scenarios, all consistent with current observational results, but between which Square Kilometre Array observations will be able to distinguish: Different cosmologies, different rates of galaxy evolution, different population fractions as a function of flux density, and so on.

Such a model has been constructed using the known 1.4 GHz source counts (Windhorst et al. 1993; Hopkins et al. 1998) as a starting point for a preliminary investigation. Since the Square Kilometre Array will have a sensitivity enabling it to detect sources as faint as 1 μJy or even fainter, the known source counts were extrapolated down to a flux density of 1 nJy, subject to known limits on the source count slope (due to the CMB) and implied limits from the number of possible optical counterparts (Windhorst et al. 1993).

The distribution in apparent size of radio sources at 1.4 GHz has been characterised as a function of flux density by Windhorst et al. (1990), and compared with the Phoenix Deep Survey sample (a 2° diameter survey at 1.4 GHz cataloguing over 1000 sources to 0.1 mJy, see Hopkins (1997) for details) by way of verification. This distribution has been used to assign apparent sizes to a list of sources with given flux densities. The result of this is to produce a simulated distribution of sources with the same statistical properties (source counts and angular size distribution) as the real sky. The axial ratio of the simulated sources has been modelled simply by a uniform distribution between values of 0.2 and 1, an aspect of the method which obviously needs refinement.

With the angular size and the axial ratio for each source, an image is constructed by adding elliptical gaussians at random locations and position angles. The peak value of the gaussian is defined by the flux density of the source. As a first step in refining this very simple model the source counts were divided between two populations, broadly described as "starbursts" and "AGNs." This was accomplished by using the known fraction of these populations as a function of flux density (Wall & Jackson 1997; Hopkins et al. 1998). In addition, to mimic the double-lobed nature of many real AGNs, a pair of adjacent elliptical gaussians have been used, rather than the single elliptical gaussian used for starbursts. At brighter flux densities the angular size distribution will not necessarily be valid for the AGN population.

In a simulation of a region the size and shape of the Hubble Deep Field (HDF), (Figure 3), with a flux density limit of 0.1μ Jy, over 2200 sources are predicted (a source density of $\approx 5 \times 10^9$ sr^{-1}). The different populations are indicated by the colours, starbursts being blue and AGNs being red.

There are many elements which have been neglected in this preliminary effort which it would be desirable to have included in further refinements of such modelling. One major refinement will be to base the simulations on known radio luminosity functions for different populations rather than using the source counts. This will allow the modelling of different evolutionary scenarios and cosmologies. Extending the models to cover a range of frequencies is also desirable.

However, while the initial model excludes many things, it still provides a very useful first estimation of the nature of the radio sky down to flux densities several orders of magnitude fainter than has ever been observed. As a result of the model presented, several preliminary suggestions relating to the details of the Square Kilometre Array design have been proposed. To minimise the effects of confusion a synthesised beam FWHM of about $0\farcs1$ is desirable. Also, with a field of view of a square degree, (compared to the few square arcminutes for the HDF) new techniques will need to be developed to catalogue, characterise and analyse the sheer number of sources which will be detected.

5 The Galaxy – Anne Green

To explore in depth the dynamics and evolution of external galaxies, it is helpful to remember that the galaxy we see in most detail is our own. A study of the distribution and kinematics of the gaseous phases of the Galaxy gives valuable insights into star formation rates, the evolution of metallicity and the initial mass function for comparable external systems. Of course many difficulties arise because we are located within the structure.

Galactic radio emission is seen over a very wide range of angular scales. For a future telescope that is sensitive to faint structures on many scales, the Galaxy will reveal filamentary and diffuse features which may constrain some extragalactic observations. Images of the Galaxy from the Molonglo Observatory Synthesis Telescope (MOST) show much faint, extended structure (Figure 4) (Green et al. 1998). Futhermore, this is only about 10% of the total emission received, as seen in total power images such as the 10 GHz data from Nobeyama (Handa et al. 1987). Deconvolution and sidelobe contamination will be factors to consider. Some of the science issues which may shape the technical requirements include:

- A more detailed investigation of the radio/FIR correlation through studies of faint, relic supernova remnants (SNRs). This clarifies the contribution of localized and diffuse synchrotron emission.

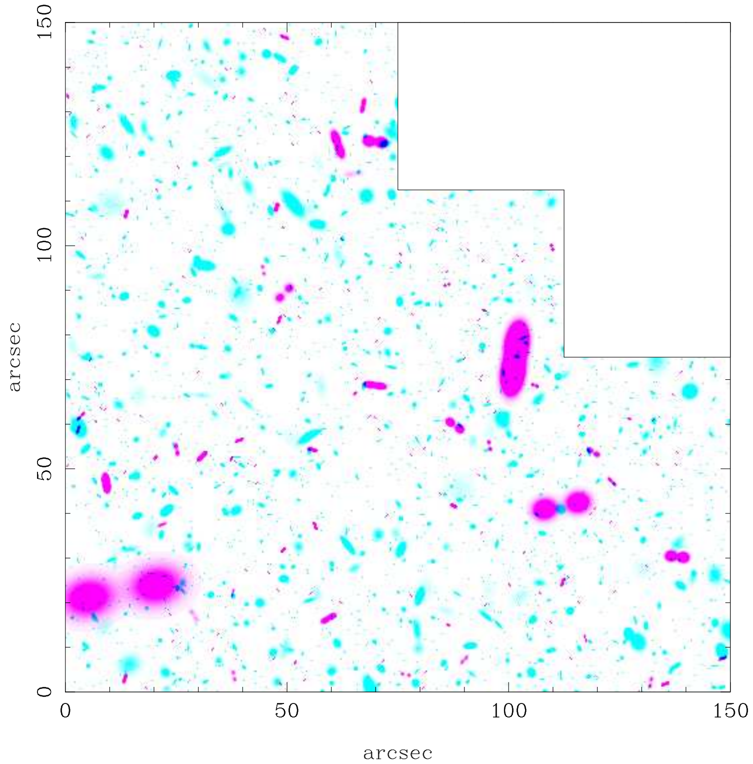

Figure 3: A simulation of AGN and starburst galaxies brighter than $0.1\,\mu$Jy at 1.4 GHz. Only 150 of the 2200 total sources predicted are AGN.

- Supernova Remnants: A search for old, evolved remnants will increase knowledge on dispersal of ejected stellar and circumstellar material, raise the number of pulsar/SNR associations as more older SNRs are discovered, and show relationships with large-scale Galactic magnetic fields. We should look for faint envelopes and other signs of interaction with the ISM, to study the evolution of the gaseous disk. Evolution of the particle population can be studied from spectral index variations. This is only effective if total flux densities are measured. Polarisation data is also more meaningful when the total power is observed.

- Shocks: The role of shocks in Galactic ecology is important. Under restricted conditions, shock excited OH masers are found when SNRs interact with molecular clouds. Magnetic field strengths along the line of sight can be measured via Zeeman splitting of the maser lines in circular polarization. The maser features may also be correlated with the sites of gamma-ray enhancements possibly connected to cosmic ray acceleration.

- HII Regions: Radio recombination lines show the distribution of ionised gas and star-forming regions in the spiral arms. Estimated distances for these regions from the radio observations cover parts of the Galaxy not available optically or with infrared telescopes because of interstellar dust extinction. It is expected that many components will be superposed along any given sight line. From theoretical considerations, the line intensities are greater at higher frequencies (in the region of 5 GHz). The partially ionised medium surrounding HII clouds can also be studied provided the dynamic range and sensitivity of the observations are high.

- Interstellar medium: Many diverse structures are seen in HI (chimneys and windblown bubbles for example). The 21 cm line is used to study these features as well as the distribution of cool, neutral gas clouds, which are seen in absorption. The large scale structure of the neutral gas can then be related to the ionised component. The dynamical interaction between the disk and halo will also be investigated.

A telescope which can complete these projects will require a broad frequency range for spectral index work (0.5 − 5 GHz). A spectral line cabability in domain near 1.7 GHz (OH lines) and 5 GHz (radio recombination lines) is also necessary, as is a bandwidth of several $100\,\mathrm{kms}^{-1}$ with velocity resolution $< 0.2\,\mathrm{kms}^{-1}$, in particular for Zeeman splitting measurements. The resolution of about 0.″1 which has been suggested is adequate, and the increased sensitivity to about $1\,\mu$Jy or better will be helpful for detecting faint structures. Total flux density measurements in intensity and polarised emission are very important for mass and energy calculations of extended sources, many of which will be on the scale of degrees.

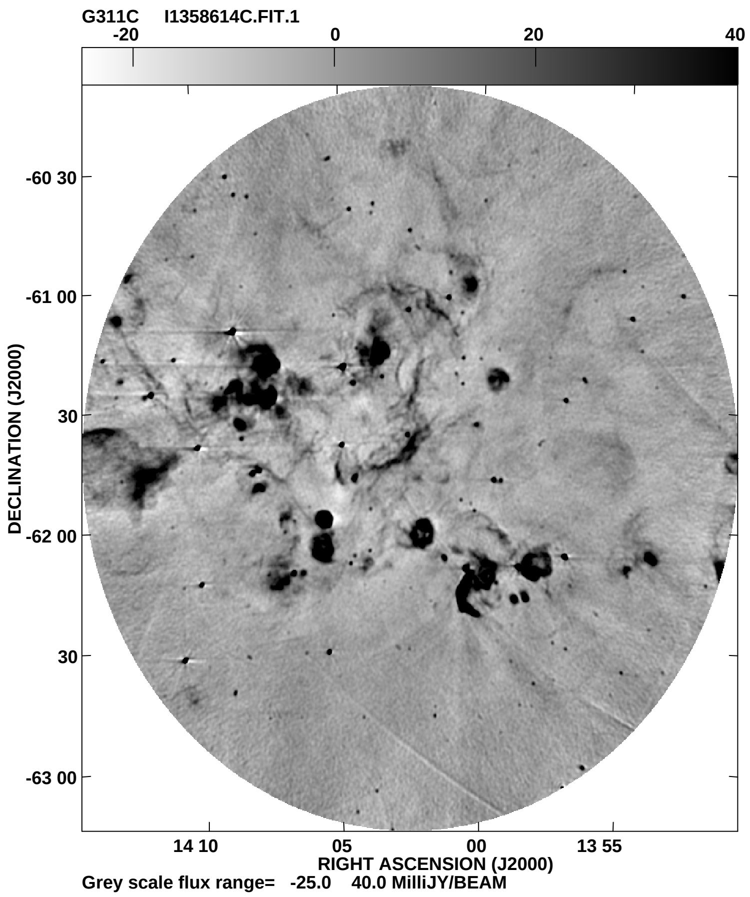

Figure 4: A MOST image of a portion of the galaxy. Note the dominance of the extended emission and filamentary structures due to HII regions and SNRs over the point sources, the extragalactic objects.

6 Radio stars – Lawrence Cram

With the sensitivity of the Square Kilometre Array expected to be around $0.1\,\mu$Jy in a 12 hour integration, the number of stars detectable through their radio emission will increase from the less than one thousand currently catalogued to more than a million. This increase allows a huge range of possible major research programs to be investigated. These programs include

- a census of the population of OB stars, allowing the initial mass function and star formation rate in our galaxy to be constrained. The mass loss rates and mechanisms (particularly the role of electrodynamics) in these stars will be able to be probed,
- observations of lower main sequence stars will enable investigations of magnetic activity and cycles, stellar flares and cosmic ray production and acceleration, as well as dK/dM and T Tauri types,
- pulsations and mass loss in cool supergiants,
- binaries with compact neutron star or black hole components, to provide valuable data on astrophysical jet phenomena as well as high energy astrophysics in general, and
- studies of the proper motions of an unprecedentedly large sample to probe the structure of the Galaxy.

The desire to observe stellar sources drives some of the instrumentation considerations. The sensitivity of the Square Kilometre Array to point sources should be maximised provided that resolution is finer than $1''$ ($L_{\rm max} > 50\,$km). In addition, many stellar studies will desire intercontinental VLBI for high angular resolution. Dynamic spectra and coincidence observations will be of interest, and these imply a need for the instrument to have high time resolution and wide-band polarimetry capabilities.

7 Pulsars – Dick Manchester

There are currently about 750 pulsars identified in the current literature. All but a handful of these are within our Galaxy, and most are within a few kpc of the Sun. Pulsars fall into two main classes: 'normal' pulsars which are typically less than 10^7 years old and have periods of between 30 ms and several seconds, and 'millisecond' pulsars, which typically have periods of between 1.5 and 20 ms and are believed to be 'recycled' or spun-up by accretion in a binary system. Most known pulsars are in the Galactic disk, but a significant population of millisecond pulsars is found in globular clusters. Estimates based on previous large-scale searches show that the total number of potentially detectable normal pulsars in the Galaxy is at least 30,000. Surprisingly, the total number of potentially detectable millisecond pulsars is at least as large. Existing searches have had limited sensitivity to millisecond pulsars, so they form less than 10% of the known pulsar population.

Large-scale searches for pulsars are undertaken for several reasons. Most obviously, they increase the number of known pulsars, allowing better determinations of the underlying pulsar population, and a larger sample for various studies of, for example, the pulse emission process, associations with supernova remnants, and the interstellar medium. However, a major motivation for such searches is the likelihood of finding unusual or unexpected types of pulsars. Pulsar astronomy has a history of such finds, for example, the first binary pulsar, the first millisecond pulsar, the first pulsar with a main-sequence companion, the first extra-solar planetary system etc. Many of these finds have important consequences, none more so that the Hulse-Taylor binary PSR 1913+16 (Taylor & Weisberg 1982), which has been used to verify general relativity and give the first observational evidence for gravitational radiation. Future searches will undoubtedly uncover new and exciting objects.

Essentially all pulsar observations are sensitivity limited – confusion is not a problem with pulsars. With its large collecting area, the Square Kilometre Array will have a major impact on pulsar astronomy. For purposes of comparison, we scale the parameters of the current Parkes Multibeam survey. This has a frequency of 1.4 GHz and a bandwidth of 288 MHz in each of two polarisations. This frequency is about optimum for many pulsar studies as it avoids the worst of the interstellar effects such as dispersion and scattering, but is not so high that pulsar flux densities are too weak.

In a full tied-array mode, in one minute, the Square Kilometre Array will give a 3σ detection of a pulsar with a mean flux density of $1\,\mu$Jy. Even if only part of the array (e.g., a compact central portion) can be used in this mode, the sensitivity will be very high. This will form a powerful instrument for studies of known pulsars, including timing, polarisation, individual pulse studies, etc. To exploit it fully, the array should provide 10 or more beams within an area of at least 1 square degree, with full Stokes parameters, high time resolution (better than $100\,\mu$s) and good frequency resolution (at least 1000 frequency channels across the band).

Searching is probably best done by incoherently summing the output of a number of subarrays. This involves some loss of sensitivity, but at least for a disk population, this is exactly compensated for by the increased area searched. Furthermore, it is not possible to arbitrarily reduce the time spent on each beam area as the sensitivity is increased, as a large number (say at least 10^3) pulse periods must be observed to provide period discrimination. A good compromise would be to incoherently sum the outputs of 100 subarrays, each equivalent to a 110 m dish and having a beam area of about 0.15 square degrees. With this system, a search along the Galactic Plane, similar to that of the Parkes Multibeam survey but with 10 times the sensitivity, would detect about 5000 pulsars with 4 min/beam or a total time of about 40 days. Depending on the back-end system, this survey could also detect a similar number of millisecond pulsars. Globular clusters would also be an attractive target; for example, in a few hours it should be possible to detect more than 100 millisecond pulsars in the core of 47 Tucanae!

It is clear that the Square Kilometre Array can be a superb pulsar machine. However, careful thought will have to be given to the optimal way to provide high time and frequency resolution in the various configurations. Polarisation properties are also crucial for pulsar applications.

8 Masers and spectral lines – Ray Norris

The interest in masers stems primarily from their use as tools to investigate the kinematics of regions containing them.

The most spectacular such use was the discovery that the H_2O masers in NGC 4258 are confined to a thin molecular disk, only 0.5 pc in diameter, surrounding the central engine (Figure 5). This discovery has provided the best evidence to date for the existence of massive black holes (MBH) in active galactic nuclei (AGN). As a result, H_2O megamasers are now becoming one of the most powerful tools available to us for probing the inner parsecs of active galaxies, for example providing a mass estimate, accurate to a few percent, of the MBH, and exploring the turn-on of the radio jet a fraction of a parsec from the MBH. The Square Kilometre Array will allow us to detect and study such megamasers up to a redshift of 0.5, and thus allow us to explore the properties of the MBH as a function of galaxy type and evolution.

As a result of enormously increasing the number of objects known to contain a MBH, many other questions will be able to be addressed. Do megamasers occur only in Sy2 and Liners, or in other galaxy types too? Does the mass of the MBH vary with redshift? Are the large black holes a result of many mergers of small black holes, or do small gas-rich galaxies already contain large black holes? Can we see accretion disks around black holes in merging galaxies? Can we trace the kinematics as the black holes merge? With the Square Kilometre Array we will also be able to study the kinematics of the accretion disc, and thus mechanism for fuelling the MBH.

To detect water megamasers the proposed instrument needs to have a frequency range extending up to 22 GHz. Methanol masers, at 6.7 GHz, could be used as a tracer of circumnuclear star formation in galaxies. The most luminous Galactic methanol masers (G340.78-0.10) would have a flux density of 2.6 mJy in NGC 253. The Square Kilometre Array could detect these with a signal-to-noise ratio of about 5 in 3 seconds.

Other maser work has concentrated on the life and death-processes of stars, using masers in the interstellar and circumstellar environment to map the kinematics and properties of the accreting or outflowing gas. The Square Kilometre Array will enable us to extend this work to nearby galaxies, so we can compare star formation processes in our own galaxy with those in starburst galaxies such as NGC 253.

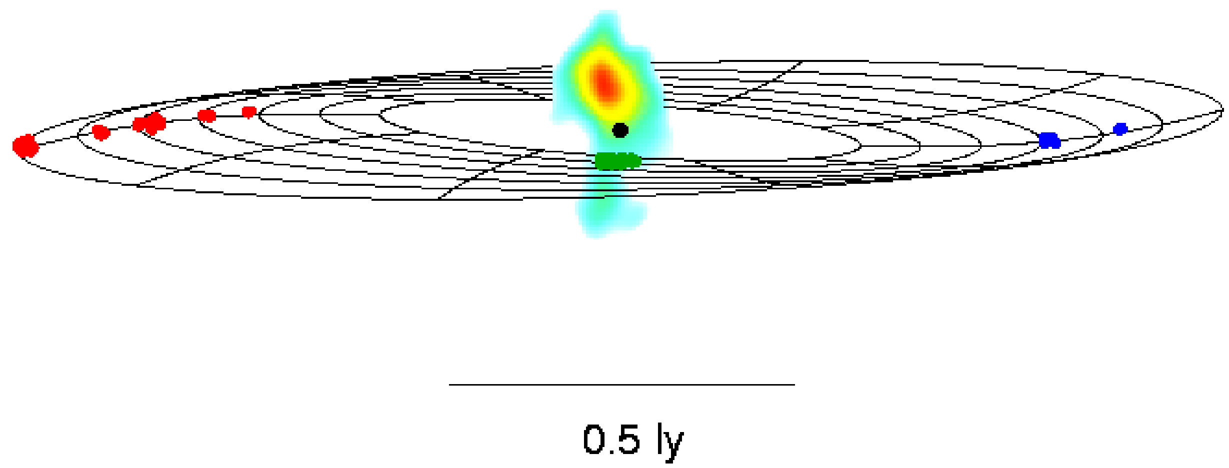

Figure 5: This image shows the geometrical relationships of the jet emission, the disk of water molecules and the black hole at the centre of the galaxy NGC 4258. The false colour image shows the relative intensity of radio emission from the jets. The large black dot indicates the location of the black hole. The dots in the disk indicate the location of water maser "spots" observed with the VLBA. All components are to scale; the scale bar indicates 0.5 light years (Herrnstein et al. 1997).

9 Concluding remarks

There are many astrophysical questions which will be addressed by the Square Kilometre Array, and only a few have been touched on in the course of this workshop. Even in the topics which have been addressed, limitations of time prevent an exhaustive debate of the possibilities. Nevertheless, it is clear that such an instrument is desirable and even necessary to significantly further our knowledge of the universe.

The broad technical specifications for the Square Kilometre Array are now starting to be refined. The primary conclusion to come out of the "Sub-microJansky Radio Sky" workshop was to re-derive the majority of the initial specifications, as well as providing a review of selected elements of Square Kilometre Array scientific goals. The proposed instrument will add considerably to the understanding of the Universe, following on from existing work in almost all branches of astronomy and astrophysics, in particular many aspects of the broad fields of cosmology, galaxy formation and evolution, and star formation and evolution.

A document summarising the science case for the Square Kilometre Array will be produced following the meeting in Calgary in July 1998. Here the technical details for the instrument will be brought into debate again, and refined in light of the achievable technical goals given the time-frame for completion of the Square Kilometre Array.

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