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Opportunities for maser studies with the Square Kilometre Array

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Abstract. The Square Kilometre Array (SKA) is the radio telescope of the next generation, providing an increase in sensitivity and angular resolution of two orders of magnitude over existing telescopes. Currently, the SKA is expected to span the frequency range 0.1−25 GHz with capabilities including a wide field-of-view and measurement of polarised emission. Such a telescope has enormous potential for testing fundamental physical laws and producing transformational discoveries. Important science goals include using H_2O megamasers to make precise estimates of H_0, which will anchor the extragalactic distance scale, and to probe the central structures of accretion disks around supermassive black holes in AGNs, to study OH megamasers associated with extreme starburst activity in distant galaxies and to study with unprecedented precision molecular gas and star formation in our Galaxy.

1. Overview

The Square Kilometre Array (SKA) is a paradigm-shifting radio telescope for the next generation, providing an increase in sensitivity and angular resolution of two orders of magnitude over existing telescopes. It will be a truly global machine with an expected lifetime of at least 50 years. Such a telescope has enormous potential for testing fundamental physical laws and producing transformational discoveries. The aim of the telescope is to answer some of the "big" questions in astronomy, such as what is the nature of dark energy, are we alone in the Universe, how did galaxies and black holes form, what is the origin and evolution of cosmic magnetism, can pulsars be used to detect gravity waves?

The project is an international consortium of 50 institutions, spread over 17 countries. Present governance is through the International SKA Steering Committee, with 21 members, which oversees the International SKA Project Office and 6 targeted Working Groups. Engagement with inter-governmental agencies has begun to establish a governance model and funding strategies. Currently, there are several pathfinder and demonstrator projects in progress for both science and technology developments.

2. SKA Concept

The concept of this instrument is based on the following principles:

• A data network of sensors of the electromagnetic field are connected using a correlator to produce an interferometric array.

• The sensing antennas will be highly concentrated in a central core, with 20% of the collecting area within 1 km, 50% within 5 km and 75% within 150 km. Outlier stations will be distributed at distances up to at least 3000 km from the core.

• Antennas and stations will be connected via wide-band optic fibre links (data rates at 100 Gbits/sec) to the central processor, which will need to process 10 – 100 Pflops/sec.

• The telescope will be built in stages, with Phase 1 planned to be 10% of the total collecting area and able to undertake unique science.

3. Status at March 2007

Following a rigorous and objective assessment, two sites to host the SKA have been shortlisted for further evaluation and development. The locations encompass Australia and New Zealand, and South Africa with 7 partner countries. The key issues in the site selection process were a very low RFI environment, a large unencumbered site and low ionospheric and tropospheric turbulence. A site decision is expected about 2010 with the complete SKA operational in 2020.

A second milestone was the selection of a Reference Design, which was developed to focus engineering and science efforts, to provide the basis for detailed costing models and to provide a recognisable image for the SKA. The design is likely to evolve, but at present it comprises small dishes with smart feeds with aperture arrays for the lower frequencies.

4. Expected capabilities

The current SKA model has an estimated cost of about 1 Billion Euro for construction with an annual operating budget of about 70 Million Euro. This is based on the following intended capabilities and specifications:

• A sensitivity at least 50 times more than the EVLA. This will enable detection of atomic hydrogen and other molecules right to the edge of the Universe. The specifications are for a continuum sensitivity of 0.4 μJy in 1 hour and a spectral line sensitivity of 5 μJy/channel after 12 hours (both 5σ detections). To achieve this requires a *very large collecting area,* $\sim$ *1 square kilometre.*

• A fast survey speed, up to 10,000 times better than currently possible. This requires a *very large field of view, projected to be 1 square degree at 1.4 GHz and 18 square arcminutes at 20 GHz.*

• A *wide frequency range of 0.1 – 25 GHz*, to handle the key science priorities.

• Moderately high angular resolution to make detailed images of structures including disks, outflows and planetary gaps. To do this requires *a large physical extent, at least 3000 km*, to produce beamsizes of $20/f_{GHz}$ mas. The size is limited by the Earth, if one assumes a real-time connected ground-based array.

• Good spectral resolution, with *more than 4000 dual polarization channels* to give velocity resolution of at least 0.2 km/sec.

5. Science goals for maser research

The strength of the SKA will be its great sensitivity with a wide field of view. Angular resolution is constrained by the size of the Earth. There are two main threads for the maser science projects, namely, one which focuses on the early Universe, dark energy and galaxy evolution, and one which will make discoveries in our Galaxy on star formation mechanisms and the interstellar medium.

5.1. *Masers in the early Universe*

Megamasers (MM) of the OH and H_2O molecules will be used to study the properties of prominent populations of active galaxies at cosmological distances. Extragalactic masering activity relies on amplification of radio continuum by foreground pumped molecular gas and the large pathlengths in galactic nuclei.

H_2O MMs are a signpost of AGN activity that may be used to study dark energy, make precise estimates of H_0 to anchor the extragalactic distance scale, and to probe the central structures of accretion disks around supermassive black holes (see Greenhill, these proceedings). Direct mapping of nuclear Keplerian disks such as found in the archetypal NGC 4258 (e.g. Claussen *et al.* 1984, Nakai *et al.* 1993, Haschick *et al.* 1994, Herrnstein *et al.* 1999) will enable determination of precision distance scales out to about 500 Mpc. For unresolved nuclear disks, observed velocity drifts and rotation velocities will extend this distance scale, albeit with less precision, well into the Hubble flow. More than a 1000 water masers may be detected to a flux limit of about 10 mJy (see Braatz et al., these proceedings, for current catalog). The most distant H_2O maser found to date is in quasar SDSS J0804+3607 at a distance of 2.4 Gps (Barvainis & Antonucci 2005), which shows that molecular gas exists at very early epochs. A second class of H_2O MM probes the interaction between radio jets and encroaching molecular clouds away from the AGN, such as seen in nearby NGC 1052 (Claussen *et al.* 1998) or Mrk 34 at a distance of 205 Mpc (Henkel *et al.* 2005) or the FR-II radio galaxy 3C 403 (Tarchi *et al.* 2003).

Powerful OH MMs are associated with extreme starburst activity in (ultra-)luminous infrared galaxies (ULIRGs) resulting from mergers and interactions (see Darling, these proceedings). The redshift distribution of these dusty starburst galaxies reflects the galaxy merger history of the universe (Townsend *et al.* 2001, Briggs 1998). The SKA can probe this population of ULIRGs up and beyond its peak at redshifts between 2 or 3. Typical extended OH MM emission structures can be imaged up to redshifts of 0.6. Powerful OH Gigamasers in the most luminous ULIRGs have been detected and imaged out to redshifts of 0.265 (Baan *et al.* 1992, Darling & Giovanelli 2001, Pihlström *et al.* 2005). The FIR radiation field provides the pumping for the OH molecules and masering action increases with the FIR luminosity (Baan 1989, Henkel & Wilson 1990). The OH emission traces the filaments and cloud in the nuclear ISM and the toroidal structures of 60-100 pc that may surround the nucleus (Rovilos *et al.* 2003, Klöckner *et al.* 2003). The properties of the prototype OH MM Arp 220 are described elsewhere (Baan, these proceedings). The OH MM emission also probes starburst-related outflows and the surroundings of the population of supernovae and SNR in the nucleus (Rovilos *et al.* 2005, Lonsdale *et al.* 2006). The nuclear emission studies of OH MM complement similar studies with ALMA.

5.2. *Galactic and extragalactic masers of many flavours*

The SKA will be used to study with unprecedented precision molecular gas and star formation in our Galaxy and nearby galaxies. There are no massive stars in the solar neighbourhood and the increased sensitivity will enable detection of large numbers of protostellar Keplerian disks and mapping of outflows. Molecular masers are common in the vicinity of newly formed massive stars, and H_2O and CH_3OH are signposts of massive star formation and some 70% of UCHIIs in the Galaxy are associated with H_2O masers (Churchwell *et al.* 1990, Walsh *et al.* 1998, Minier *et al.* 2000). Observations with multiple species of masers will complement the studies of young stellar objects, ultra-compact HII regions, and evolved stars. We will be able to confirm that Class II methanol masers are not found near low-mass stars.

One exciting possibility will be to image directly stellar photospheres and stellar winds in AGB stars and to detect eclipsing planets. Another key science objective will be to make precision distance measurements in the Galaxy, which will determine peculiar motions in the spiral arms and resolve many apparent discrepancies in distances to particular objects (e.g. Xu *et al.* 2002). Proper motions and parallax measurements will be routine for a large number of sources.

Systematic and detailed studies of extragalactic masers associated with evolved stars and star formation will be possible with the sensitivity and resolution provided by SKA. For instance, the properties of 1720 MHz OH masers measured in nearby spiral galaxies such as M33 (expected source fluxes of 3 mJy at a distance of 1 Mpc) can be correlated with those associated with supernova remnant (SNR)-molecular cloud interactions in our Galaxy (e.g. Frail *et al.* 1996, Yusef-Zadeh *et al.* 1996). Extragalactic H_2O kilomasers may trace weak nuclear activity (as in H_2O MM) or massive star-forming regions. NGC 2146 shows that H_2O emission from UCHII regions may be detected up to distances of 50 Mpc (Tarchi *et al.* 2002).

6. Conclusions

A summary of what the SKA is likely to produce for maser science include:

• A large increase in the number of sub-parsec disks around AGNS to be used to study structure and black hole properties. There will be a big improvement in sensitivity but the distance limit remains unchanged at about 500 Mpc.

• Probing high density gas in parsec nuclear regions of high redshift galaxies, with no distance limit. For resolved disks, an outcome will be precision distances and an improved measure of H_0.

• Many more disks and outflows detected for star-forming regions and dusty proto-clusters in our Galaxy. Masers associated with SNRs will be studied in nearby galaxies.

• Proper motion and parallax studies will give a more precise picture of the structure and peculiar motion of the spiral arms in our Galaxy.

A more detailed explanation can be found in *"Science with the Square Kilometre Array"*, edited by Carilli & Rawlings in New Astronomy Reviews (2004) volume 48.

References

Baan, W. A. 1989, *ApJ* 338, 804

Baan, W. A., Rhoads, J., Fisher, K., Altschuler, D. R. & Haschick, A., 1992, *ApJL*, 396, L99

Barvainis, R. & Antonucci, R. 2005, *ApJ* (Letters) 628, L89

Briggs, F. H. 1998, *A&A* 336, 815

Churchwell, E., Walmsley, C.M. & Cesaroni, R. 1990, *A&AS* 83, 119

Claussen, M.J., Heiligman, G.M., & Lo, K.Y 1984, *Nature* 310, 298

Claussen, M.J., Diamond, P.J., Braatz, J.A., Wilson, A.S. & Henkel, C. 1998, *ApJL* 500, L129

Darling, J. & Giovanelli, R., 2001, *AJ*, 121, 1278

Frail, D.A., Goss, W.M., Reynoso, E.M., Giacani, E.B., Green, A.J. & Otrupcek, R. 1996, *AJ* 111, 1651

Haschick, A.D., Baan, W.A. & Peng, E.W. 1994, *ApJL*, 437, L35

Henkel, C., Peck, A.B., Tarchi, A., Nagar, N.M. *et al.* 2005, *A&A* 436, 75

Henkel, C. & Wilson, T. L. 1990, *A&A* 229, 431

Herrnstein, J.R., Moran, J.M., Greenhill, L.J., Diamond, P.J., *et al.* 1999 *Nature* 400, 539

Klöckner, H.-R., Baan, W.A., & Garrett, M.A. 2003, *Nature*, 421, 821

Lonsdale, C.J.,Diamond, P.J., Thrall, H., Smith, H.E. & Lonsdale, C.J. 2006, *ApJ*, 647, 185

Minier, V., Booth, R.S. & Conway, J. 2000, *A&A* 362, 1093

Nakai, N., Inoue, M., & Miyoshi, M. 1993, *Nature* 361, 45

Pihlström, Y.M., Baan, W.A., Darling, J. Klöckner, H.-R. 2005, *ApJ*, 618, 705

Rovilos, E., Diamond, P.J., Lonsdale, C.J., *et al.* 2003, *MNRAS*, 342, 373

Rovilos, E., Diamond, P. J., Lonsdale, C.J. *et al.* 2005, *MNRAS*, 359, 827

Tarchi, A., Henkel, C., Peck, A.B., Menten, K.M. 2002, *A&A* 389, L39

Tarchi, A., Henkel, C., Chiaberge, M., Menten, K.M. 2003, *A&A* 407, L33

Townsend, R.H.D., Ivison, R.J., Smail, I., Blain, A.W., Frayer, D.T. 2001, *MNRAS* 328, L17
Walsh, A.J., Burton, M.G., Hyland, A.R. & Robinson, G. 1998, *MNRAS* 301, 640
Xu, Y., Reid, M.J., Zheng, X.W., Menten, K.M. 2006, *Science* 311, 54
Yusef-Zadeh, F., Roberts, D.A., Goss, W.M., Frail, D.A., Green, A.J. 1996, *ApJL* 466, L25