FULL TITLE
ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION**
NAMES OF EDITORS

Science with the next generation of radio surveys from LOFAR to the SKA

Matt J. Jarvis

Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK

Abstract. Over the next few years the new radio telescopes, such as the Low Frequency Array (LOFAR) will greatly enhance our knowledge of the active history of the Universe. Large-area surveys with these new telescopes will no longer be dominated by the powerful active galactic nuclei, but by radio-quiet quasars and star-forming galaxies over all cosmic epochs. Further in the future ($\sim$ 2014) the Square Kilometre Array (SKA) will take studies in the radio regime to a whole new level, with the ability to detect neutral hydrogen via the 21 cm transition over the majority of cosmic time. This will enable both the detailed study of individual galaxies and the use of these galaxies as probes Dark Energy. In these proceedings I give an overview of the science goals behind these new radio telescopes, with particular emphasis on galaxy evolution and cosmology. Finally I briefly discuss the SKA science simulation effort.

1. Introduction

During the last half century our knowledge of the Universe has been revolutionised by the opening of observable windows outside the narrow visible region of the spectrum. Observations from the radio to γ-rays have provided new and completely unexpected information about the nature and history of the Universe and have resulted in the discovery of a cosmic zoo of strange and exotic objects. At this meeting we have seen the exciting results that are now coming out of the deep optical and infrared surveys being undertaken from the ground and space. In this contribution I highlight some of the major projects in the radio regime that will have the ability to significantly advance our knowledge of galaxy formation and evolution, in addition to many other science areas.

2. The Low-Frequency Array

One of the few spectral windows that still remains to be explored is at the low radio frequencies, the lowest energy extreme of the accessible spectrum.

The Low Frequency Array (LOFAR) is a revolutionary aperture synthesis array currently under construction in the Netherlands. It will operate in the $\sim$20–240 MHz (1.25–15m wavelength) range and will achieve at least 4" resolution at 200 MHz with higher angular resolution likely to materialise as a result of LOFAR being extended into Germany and the UK. LOFAR will instantaneously survey large areas of the sky using independently steerable beams. It will be 3 orders of magnitude more sensitive than previous low-frequency radio telescopes.

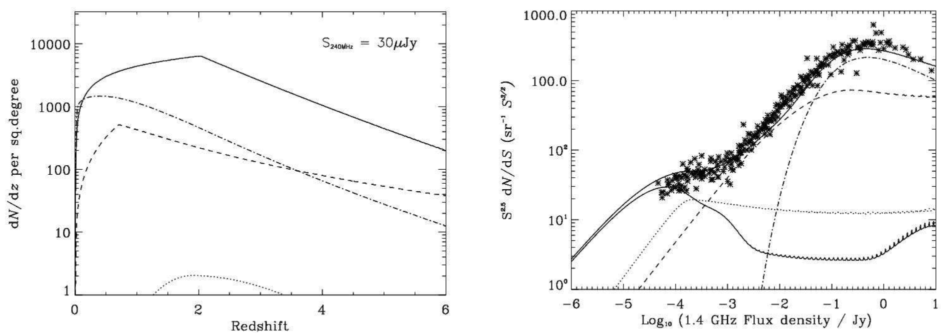

Figure 1. *(left)* The predicted number of sources per unit redshift per square degree for a typical deep LOFAR survey with a flux-density limit of 30 μJy. The various lines represent star-forming galaxies (solid), radio-quiet quasars (dot-dashed), FRI-radio galaxies (dashed) and FRII-radio galaxies (dotted). *(right)* The predicted source counts for these models with the various lines showing the FRIIs (dot-dashed), FRIs (dashed), radio-quiet quasars (dotted) and star-forming galaxies (solid). The total source counts are also represented by the upper solid line. The stars are the 1.4 GHz source counts from Seymour et al. (2004).

One of the most important areas of LOFAR will be to carry out large-sky surveys. Such surveys are well suited to the characteristics of LOFAR and have been designated as one of the key projects that have driven LOFAR since its inception. Such deep LOFAR surveys of the accessible sky at several frequencies will provide unique catalogues of radio sources for investigating several fundamental areas of astrophysics which, up until now, have been within the remit of telescopes operating at shorter wavelengths. These include tracing the star-formation history of the Universe, the formation of massive black holes, galaxies and clusters of galaxies. Moreover, because the LOFAR surveys will probe unexplored parameter space, it is likely that they will discover new phenomena.

2.1. Tracing the history of the active Universe with LOFAR

As mentioned above LOFAR will have the capability of tracing star-forming galaxies out to the highest redshifts. This has already been done with radio telescopes to a certain extent with deep, small-area ($\sim$ 1 square degree) observations with the VLA (e.g. Ivison et al. 2002), however LOFAR offers the possibility to extend such studies to $\gtrsim$100 square degree areas. This is possible due to the new technology that LOFAR is built on (see http://www.lofar.org), which enables multi-beaming over large areas. Thus the survey speed is huge in comparison to traditional dish-based interferometers operating at higher frequencies such as the VLA.

The improvement in survey speed is also helped considerably by operating at low-frequency. This is because the typical power-law slope of synchrotron radiation emitted from star-forming galaxies and AGN increases towards low frequencies. Thus, observing at low-frequencies is important to combat the $k-$correction for the higher-redshift sources.

To illustrate the massive leap in sensitivity of the LOFAR, we show in Fig. 1 the predicted number of objects per unit redshift per square degree for a proposed deep-LOFAR survey of 250 square degrees. Details of how these curves were generated for the AGN populations can be found in Jarvis & Rawlings (2004), the evolution of starburst galaxies were modelled using the luminosity function of Yun et al. (2001) with pure luminosity evolution constrained by the far-infrared sources counts of Blain et al. (1999) and the radio source counts of Seymour et al. (2004), (Jarvis et al. in prep). One can see that the powerful active galactic nuclei (AGN) traditionally found in radio surveys are in the minority in deep LOFAR surveys. Moreover it is also clear that LOFAR enters the regime where radio-quiet quiet quasars and low-luminosity Fanaroff-Riley Fanaroff & Riley (1974) class I (FRI) AGN are the dominant AGN populations over all redshifts, rather than the powerful FRII-type radio galaxies. Thus, LOFAR offers the unique opportunity to trace the majority of activity in the Universe.

However, much of the science that can be carried out with the LOFAR deep surveys will also rely on data from all of the other wavebands. Particularly, synergies with the new generation of sensitive wide-field optical and near-infrared telescopes will be crucial in identifying the sources responsible for the radio emission, such as the obscured AGN, naked AGN and starburst galaxies. These will not only lead to the identification of the radio sources, the positions of which can subsequently used for spectroscopic follow-up, but the optical and near-infrared data sets could be used to estimate redshifts for the various sub-populations. Such a data set over ~ 250 square degrees with a high areal density would thus provide the ideal input catalogue for future experiments to measure the evolution in the Dark Energy component of the Universe through Baryon Acoustic Oscillations (BAO) with instruments such as FMOS and WFMOS (e.g. Nichol 2006). Objects selected at radio wavelengths will also be much easier to obtain redshifts for due to the high probability of them having bright emission lines from either a starburst or AGN. Therefore, the time to survey the galaxy populations in spectroscopy is less than the time that would be needed to obtain redshifts from the continuum features and absorption lines that are the characteristics of the massive elliptical galaxies, which are currently being used in various current experiments (e.g. Cannon et al. 2006).

3. The Square Kilometre Array

LOFAR will have a collecting area of roughly 5 per cent of a square-kilometre array (SKA), thus it is a very important path finder experiment towards the much larger SKA telescope.

As the name suggests the SKA will have a total collecting area of 10^6 m^2, making it ~ 50 times more sensitive than the EVLA. This increase in sensitivity enables the SKA to push studies of galaxy formation and evolution to an unprecedented level as the SKA will be able to detect the 21 cm transition of neutral hydrogen in emission up to $z \sim 2$. Thus, the SKA will have the ability to trace the evolution of the HI mass function over 75 per cent of cosmic time (see e.g. Fig. 2). Even if this was conducted over relatively small areas it would still provide a great leap in our knowledge of galaxies and their dark matter haloes. However, one of the big challenges for the SKA is to couple this sensitivity to a large field-of-view of order ~ 50 square degrees. This coupling of sensitivity

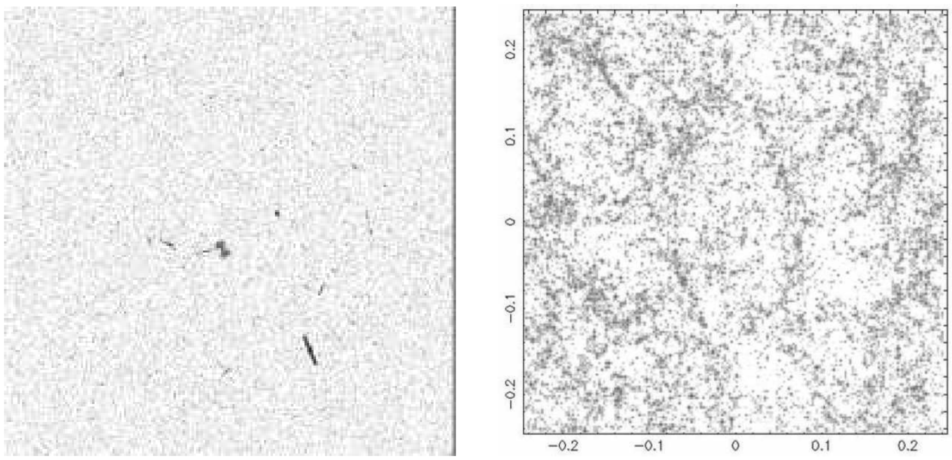

Figure 2. *(left)* A 1 square degree continuum simulation for the SKA. The flux-density limit is 1 μJy at 1.4 GHz (Jarvis et al. in prep.). *(right)* 0.25 square degree HI simulation at a redshift of $2.55 < z < 2.65$ (Obreschkow et al. in prep.) based on the Millennium Simulation (Springel et al. 2005) and the semi-analytic model of Croton et al. (2006).

and field-of-view would make the SKA the most powerful survey telescope in the world, with a survey speed around 10^4 times greater than the EVLA.

This means that within approximately one year the SKA could survey the whole hemisphere in HI up to $z \sim 2$ with the expectation of obtaining spectroscopic redshifts via 21 cm emission for $\sim 10^9$ galaxies. With such a survey the SKA would become the premier instrument for measuring the evolution of Dark Energy via BAOs (Abdalla & Rawlings 2005).

The SKA will also be able to conduct the deepest continuum observations ever made in the radio regime. Fig. 2 shows a simulated square degree of sky at 1.4 GHz for a typical deep (1μJy) continuum survey with the SKA. This shows the extent to which the SKA will be able to probe galaxy formation and evolution up to the highest redshifts, again like LOFAR the dominant sources are starbursts and radio-quiet quasars. However, the sensitivity is such that typical starburst galaxies can be detected up to and into the epoch of reionisation. If the SKA reaches it's goal with respect to the field-of-view then we expect to detect around 10^7 galaxies per 50 square degree pointing, in its deep continuum observations.

However, the SKA will not only be a redshift survey machine, the science goals are broad and span everything from the search for life on other planets through to the epoch of reionisation.

4. The SKA Design Study

The concept for the SKA has been around for almost two decades, with the first mention of it in the literature in 1991 (Swarup 1991; Wilkinson 1991; Noordam, Braun & de Bruyn 1991; Braun 1991). However, in the past few years this concept has gradually turned into a real project. The SKA design study

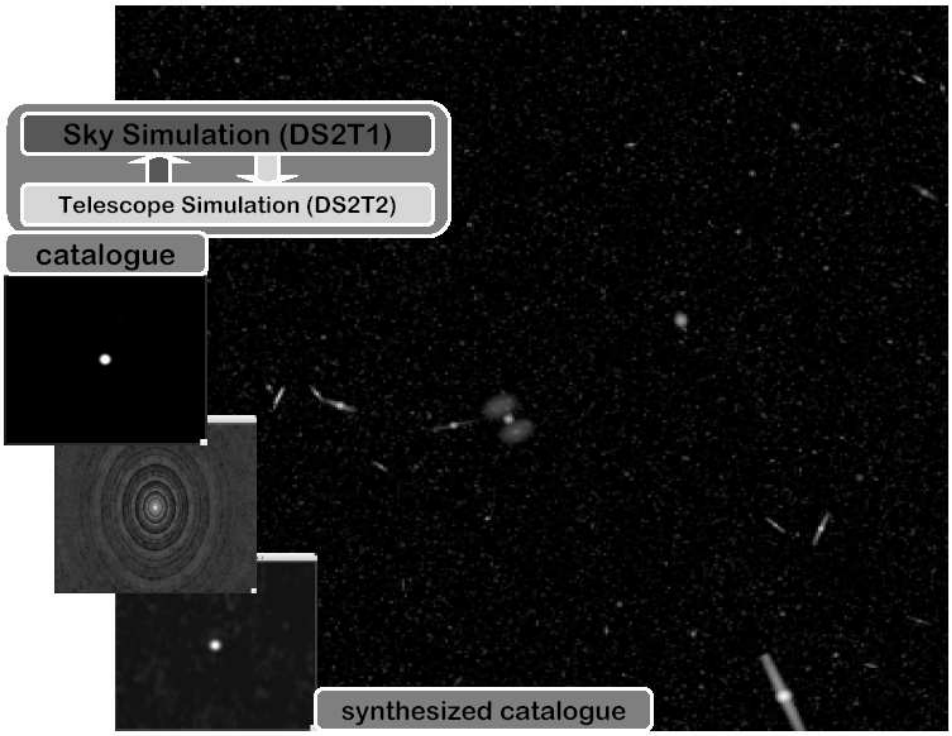

Figure 3. Schematic representation of the SKA Design Study for the science simulations, describing how a 'real sky' catalogue is put through a telescope simulator and the output is then passed back to the scientists to analyse. This is carried out for a range of SKA designs to optimise the telescope design.

is now underway across the world. This design study covers the development of the technology needed to build a SKA, however a critical component of the design study is the science simulations which will dictate the final design of the SKA.

The science simulations are predominantly being carried out in five Key Science areas. These are Cradle of Life, Probing the Dark Ages, The origin and evolution of Cosmic Magnetism, Strong field tests of gravity using pulsars and black holes and Galaxy evolution, cosmology and dark energy . In these proceedings I have only described the science concerned with galaxy formation and evolution. In this section I briefly describe the process by which the science simulations are being carried out.

The science simulations can be split into two threads, the first is concerned with both generating *real* skies (i.e. how the sky looks if we had a perfect view of it) and also the analysis of data after it has been processed through a simulated SKA telescope. This middle step of taking real skies and putting them through a simulated telescope is then carried out in the second thread. Thus, the tasks enable scientists not familiar with radio astronomy techniques to have an important input into the science simulations effort and also to realise the potential of such a powerful telescope.

A schematic representation of the interplay between the two threads within the European Design Study, called DS2-T1 (science simulations) and DS2-T2 (telescope simulations), is shown in Fig. 3. This process is now underway and will begin to produce important information which will be fed into the overall design of the SKA (see e.g. Fig. 2). These simulations will also be tested to a certain extent with other SKA pathfinder telescopes operating at higher frequencies than LOFAR, such telescopes currently under development are the South African Karoo Array Telescope (KAT; http://www.ska.ac.za/kat) and the Australian extended New Technology Demonstrator (xNTD; http://www.atnf.csiro.au/SKA/xntd.html). These will both lead up to the construction of the 10 per cent SKA planned for 2014, with completion of the 100 per cent SKA in 2020.

5. Summary

I have discussed some of the extra-galactic science that will begin to emanate from the new generation of radio telescopes, in particular LOFAR and the SKA. However, both of these instruments will make great strides in a wealth of other fields spanning astrophysics, cosmology and particle physics and the reader is encouraged to read the respective websites at (http://www.lofar.org and http://www.skatelescope.org).

Acknowledgments. I acknowledge funding from the SKA Design Study. I would also like to thank a number of people who have contributed to this article in a number of ways, these are Hans-Rainer Klöckner, Lance Miller, Danail Obreschkow, Steve Rawlings, Huub Röttgering and Richard Schilizzi.

References

Abdalla, F. B., & Rawlings, S. 2005, MNRAS, 360, 27
Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J.-P. 1999, MNRAS, 302, 632
Braun R. 1991, Early Universe Radio Observatory , Colloquium ASTRON, fall 1991
Cannon, R., et al. 2006, MNRAS, 372, 425
Croton, D. J., et al. 2006, MNRAS, 365, 11
Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31P
Ivison, R. J., et al. 2002, MNRAS, 337, 1
Jarvis, M. J., & Rawlings, S. 2004, New Astronomy Review, 48, 1173
Nichol R., 2006, in 'Cosmology, galaxy formation and astroparticle physics on the pathway to the SKA', eds. Klöckner H.-R., Jarvis M., Rawlings S., Taylor A. (astro-ph/0611801)
Noordam, J., Braun, R., de Bruyn, G., 1991, NFRA Note nr 585, September 5
Seymour, N., McHardy, I. M., & Gunn, K. F. 2004, MNRAS, 352, 131
Springel, V., et al. 2005, Nat, 435, 629
Swarup, G. 1991, CURRENT SCIENCE V.60, NO.2/JAN25, P.106, 1991, 60, 106
Wilkinson, P. N. 1991, ASP Conf. Ser. 19: IAU Colloq. 131: Radio Interferometry. Theory, Techniques, and Applications, 19, 428
Yun, M. S., Reddy, N. A., & Condon, J. J. 2001, ApJ, 554, 803