

Review



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The square kilometre array and the transient universe

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The square kilometre array (SKA) is a next generation radio telescope that will be built in southern Africa and Australasia. It will be built in two phases and will use a range of detectors, from aperture arrays to dishes, to span the frequency range from a few tens of megahertz to a few gigahertz. The combination of great sensitivity, wide field of view and unprecedented computing power mean that the SKA will be an excellent instrument for studying the transient radio universe. Transient radio emission is generated in extremes of: gravitational and magnetic fields, velocity, temperature, pressure and density. While we know about plenty of source classes for this type of short duration radio emission, there is still a large range of transient parameter space that has not yet been sampled owing to the limitations of current generation radio telescopes.

1. The square kilometre array

The detailed specifications for the square kilometre array (SKA) are still under consideration as teams around the world are working on the design, and I, therefore, present here the current working specifications. Since the time of the Discussion Meeting that this article accompanies the decision on the siting of the telescope has been made. It has been decided that the telescope will be built on two sites: southern Africa and Australasia. The telescope will also be built in two phases with SKA₁ constituting about 10 per cent of the collecting area of the complete SKA; more details of the relationship between the two phases can be found in table 1, and for up-to-date details one can refer to the SKA project website (<http://www.skatelescope.org>). We note that the existing Australian Square Kilometre Array Pathfinder¹ (ASKAP) dishes are 12 m in diameter and are fitted out with phased array feeds to give a large instantaneous

¹See <http://www.atnf.csiro.au/projects/askap/index.html>.

Table 1. The two phases of the SKA showing the numbers and type of different receptor technologies, the associated observing frequencies and the locations.

	phase 1	phase 2
dishes (0.45–3 GHz)	190 (South Africa) + 64 MeerKAT dishes 60 (Australia) + 32 ASKAP dishes	
dishes (0.45–10 GHz)		3000 (southern Africa)
low-frequency aperture array stations (0.07–0.45 GHz)	50 (Australia)	250 (Australia)
mid-frequency aperture array stations (0.4–1.4 GHz)		250 (southern Africa)

field of view and the meer Karoo Array Telescope² (MeerKAT) dishes are 13.5 m in diameter and are fitted with low-noise single pixel receivers that provide high instantaneous sensitivity. In phase 1, only intermediate baselines will be available, and in the second phase continental-sized baselines will be included. Approximately 50 per cent of the collecting area will be located in core regions of about 5 km in diameter. The specifications of most interest to the transient project are the sensitivity and the field of view. If, for reasons discussed below, we consider just the core region, the gain will be approximately $2500 \text{ m}^2 \text{ K}^{-1}$ (corresponding to a flux limit of approx. $400 \text{ } \mu\text{Jy}$ in a 1 min integration) for the low-frequency aperture arrays and approximately $5000 \text{ m}^2 \text{ K}^{-1}$ at frequencies above 1 GHz. The desired specification for the field of view at the low-frequency end of the spectrum is 200 square degrees, while in the mid-frequency range the aim is for a minimum of 1 square degree, up to as much as 200 square degrees and at frequencies above 1 GHz the aim is for 1 square degree.

One of the challenges of using the SKA for high time resolution studies is the need to make the trade-off between temporal and angular resolution. The SKA is an interferometer and is thus made up of lots of elements which are separated by average distances that are large compared with the individual element sizes. This distributed nature is required so as to achieve high image fidelity and angular resolution when making maps of the sky. In order to achieve acceptable data rates when the telescope is in the so-called ‘imaging’ mode, the data are averaged in the correlator to a time resolution of the order of seconds, which, as we will show below, is insufficient to study the most extreme transient phenomena. Instead of using a correlator to study these sources, it is therefore necessary to use a technique called beam-forming, in which the signals from each of the elements are added together in phase. If the elements are widely separated, then this beam on the sky will be very small, say, for the core of the SKA at 1 GHz, just 14 arcseconds. While this is perfectly acceptable, and even desirable for observing known sources, it is very small compared with the available field of view. For optimizing transient detections, we need to maximize the product of field of view and observing time. The total number of beams required to sample the entire available field of view of an element is simply the square of the ratio of the separation of the elements over the element size. For the SKA, this is many thousands, indicating the size of the computing challenge that comes with optimally using the SKA for high time resolution surveys of the sky. There is a more detailed discussion of some of the computing requirements presented in Smits *et al.* [1]. Discussions on how to further make optimizations between sensitivity and field of view for transient searches, using the different observing modes, such as sub-arraying, fly’s eye and trading beams for bandwidth, are presented in Colegate & Clarke [2] and Macquart [3].

2. Opportune moment for radio transients

Until relatively recently, there have been few comprehensive surveys of the large transient phase space using radio telescopes. This is mainly because the combination of sensitivity, field of view

²See <http://www.ska.ac.za/meerkat/>.

and time on the sky required to sample it was difficult to realize simultaneously. Moreover, the time scales of these transient sources can vary from nanoseconds to seconds (see table 1 for the range of neutron star variability time scales, for example) and some of them may show complex structures in the frequency–time plane. Significant progress has been made with the advent of the multi-beam receivers that have been placed on the single dish telescopes, such as Parkes [4] and Arecibo [5]. These have been particularly successful in catching new phenomena such as rotating radio transients (RRATs; [6]) and the so-called Lorimer burst [7]. However, the rareness of these sources also indicates that further improvements, particularly in field of view, are required in order to discover more of these sources and new source classes.

To achieve these improvements, one needs the right combination of different technologies. Some possibilities include the use of many small dishes or sparse or dense aperture arrays. All of these technologies and ideas are being tested in some form or other with the SKA pathfinders and precursors. The low-frequency aperture arrays are being tested in the low-frequency array (LOFAR; e.g. [8]), Murchison widefield array [9] and the long-wavelength array [10]. When using dishes, it is possible to either choose to increase the field of view further by using a phased array feed, as is being done in Aperture Tile In Focus (Apertif; [11]) and ASKAP [12], or by improving the sensitivity by using receivers with low system temperature, as is being done with MeerKAT [13]. As discussed above for the SKA, the use of many small elements that are widely distributed means that we need to take advantage of vast computing resources to be able to sample a sufficient fraction of the sky. However, these so-called software telescopes do provide a large and flexible array of observing modes (see, for example, the different beam formed modes for LOFAR described by Stappers *et al.* [8]).

It is important to note that, in general, radio astronomers have tended to use the word ‘transient’ as a pseudonym for any time variable source that is not on all the time. The search is definitely on to find more true transient events, i.e. those that only occur once, such as the Lorimer burst, but other repeating objects such as the RRATs are also very interesting. These different classes of sources may share similar detection strategies, but they may require different optimal observing strategies. The discovery of truly transient events relies on having excellent instantaneous sensitivity. There is no point in integrating for longer on these objects to improve sensitivity, so one cannot therefore afford to trade integration time for field of view in this case. This is a crucial distinction when compared with surveys for pulsars, for example. As pointed out by Macquart [3], the fact that transients typically have a duration that is much shorter than the telescope dwell time (figure 1) means that trying to slew the telescopes to catch more events will not increase sensitivity. The situation is different for external triggers, particularly from events initially detected at high energies. This is because radio emission has a frequency-dependent dispersive delay as it passes through the interstellar medium. As a result, there is a delay, of up to seconds, between an event being detected at high energies or as a gravitational wave source and the arrival of any associated radio emission. This would then provide the opportunity to ‘slew’ the telescope, in particular for aperture arrays where pointing directions can be changed more rapidly than for dishes, to be on source in time to catch the event in the radio. This could be particularly interesting for determining the distance of extragalactic events and characterizing the intergalactic medium. Another consequence of this is that having a buffer able to store the data over a larger field of view than can be accessed in real time, like the transient buffer boards of LOFAR [14], will be very useful.

3. Transients and parameter space

The time–luminosity phase space for the range of different radio transients is well described by the plots presented in fig. 9 of SKA Memorandum no. 97 [15]. It shows that, in both dimensions, the range of possible sources spans more than 20 orders of magnitude. The known ‘transient’ sources make up only about 10 per cent of the phase space and are dominated by the radio pulsars and their different types of emission (see also figure 1). Cordes [15] also shows where a number of proposed sources (which we will look at in a little bit more detail below) lie in parameter

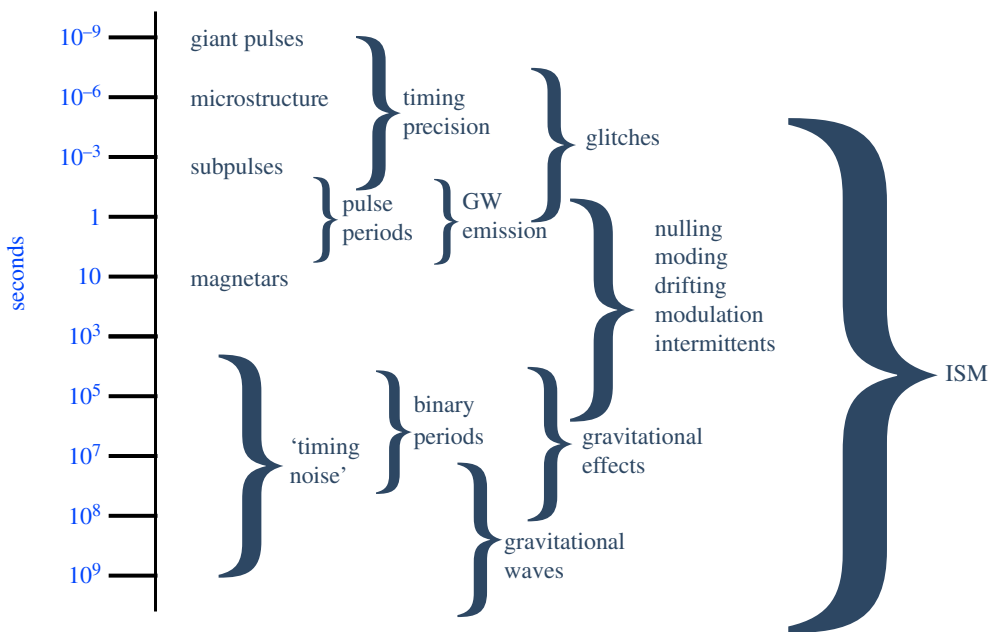


Figure 1. The range of time scales over which neutron stars show variations in the properties of their radio emission that could be detected with the SKA. These range from the giant pulses from the Crab pulsar, which last just a few nanoseconds, to the interstellar medium (ISM), which can cause variations over almost the entire span of time scales. (Online version in colour.)

space. Also indicated are the apparent brightness temperatures associated with these events, and it is apparent that the majority of them lie above the canonical 10^{12} K temperature limit, which is associated with the inverse Compton effect that is relevant to incoherent synchrotron sources. This value is usually considered to separate ‘coherent’ and ‘incoherent’ emission mechanisms and indicates that the fastest transients are typically associated with coherent emission. This is nicely complementary to the greatly increased phase space that is being probed so successfully by ongoing optical surveys; for example, the Palomar Transient Factory [16], the Catalina Real-Time Transient Survey [17] and Panoramic Survey Telescope and Rapid Response System [18], and the extremely ambitious project planned for a similar time scale to the SKA, the Large Synoptic Survey Telescope.³ These surveys have cadences that extend from as short as a minute up to days. They are aimed at similar cataclysmic events to the radio observations, but generally probe different physics from the fast radio transients in particular. The possibility of the multi-wavelength, and multi-messenger when we include gravitational waves, detection of these transients will provide us with a very rich set of data with which to understand the physics of these extreme objects.

If we consider a somewhat arbitrary cut-off of 1 s to separate transients (using the loose definition discussed above) that occur on longer time scales, and therefore may be detected in either the time domain processing or in the comparison of fluxes in images, from those that are best studied through the use of beam-formed observations with high time resolution, we can make the lists of known and potential sources given in table 2.

Let us consider just a few of these sources in a bit more detail. The prototypical transient radio sources are the radio pulsars, and yet there is still much to learn about radio emission from neutron stars. In the last few years, we have seen a significant increase in the range of radio-emitting neutron stars and their variability, e.g. RRATs, intermittent pulsars [19,20], radio-emitting magnetars [21] and more, as shown in figure 1.

³See <http://www.lsst.org/lsst/>.

Table 2. A list of just some of the known, postulated and as yet unidentified sources of transient radio emission that could be detected with the SKA.

'long'	'short'
X-ray binaries and jet sources (e.g. YSOs)	ultra-high-energy particles
ultra-luminous X-ray sources	the Sun (type II and III bursts)
extreme scattering events	annihilating black holes
active galactic nuclei	extragalactic bursts (e.g. Lorimer)
burpers (e.g. GCRT 1745-3009)	coalescing neutron stars
gamma-ray bursts	
brown dwarfs and symbiotic binaries	
.....	
supernovae and flare stars	
planets (solar and extrasolar)	
neutron stars (intermittent pulsars/magnetars/RRATs)	
electromagnetic counterparts to GW sources	
.....	

A very exciting development is the possibility of having the advanced LIGO and VIRGO gravitational wave detectors operating at the same time as the SKA precursors and then with SKA itself. The increased volume of the Universe which these detectors will be sensitive to almost guarantees that they will make direct detections of gravitational waves in the near future. Unfortunately, though, the positional accuracy that they will be able to achieve is still relatively poor. This is where the wide field and rapid slewing capabilities of the next generation of radio telescopes becomes very important, allowing for the possibility of detecting the electromagnetic counterpart to the gravitational wave source. Not only will this be additional evidence to support a detection, it will also provide additional information on the gravitational wave source. Radio observations in particular have some advantages over other wavelengths. For example, radio emission is unobscured by dust, and it is also possible to observe during the day. Some work on trialling these sorts of experiments has already been undertaken between the LIGO Science Consortium and LOFAR [22] and also with the Karl G. Jansky Very Large Array [23]. It is important to note that it will also be of interest to look at archival data obtained with the gravitational wave detectors based on detections of transients made in the radio. This may allow deeper searches of the gravitational wave data, for example.

The 5 ms duration isolated burst of radio emission detected by Lorimer *et al.* [7] in archival data taken while surveying the Magellanic Clouds has transformed our thinking about radio transients. The source was detected in a pointing well away from the small Magellanic Cloud and at a dispersion measure that indicated that it was located at a redshift of approximately 0.2, suggesting that it was truly extragalactic. While there are some questions about the authenticity of the burst owing to the presence of some pernicious interference seen at a similar dispersion measure [24], it has not been conclusively ruled out. Recently, Keane *et al.* [25] discovered another bright single burst with duration less than 7 ms and a dispersion measure of approximately $750\text{ cm}^{-3}\text{ pc}$, which, if extragalactic, would place it at a similar redshift. Despite the fact that the burst did not repeat in 15 h of follow-up observations, as the burst is closer to the galactic plane there is a small chance that it is galactic. The way forward with these objects is clearly to find more: the expected rates are somewhat uncertain because they are extrapolated from just a couple of sources, but there should be a couple of hundred in the sky per day. While this sounds large, it does still require a large field of view to be able to detect a few on a reasonable time scale with only the large multi-beam surveys with Arecibo and Parkes currently providing a reasonable probability of detection. Extending the sample will allow an improved determination of the luminosity distribution and thus help with determining the source population. So far, these

sources have only been found in post-processing, and therefore another key aim will be to try to find the sources in real time, allowing one to undertake multi-wavelength follow-up.

4. The present and near future

En route to the SKA, there are a number of important programmes being undertaken or planned for studying the transient radio universe. It is now standard practice to undertake searches for single or repeating dispersed bursts of emission as part of the processing of pulsar surveys, and these are already revealing new RRATs [5,26,27]. New dedicated surveys for transients have also been undertaken recently. Using the Allen Telescope Array (ATA), Siemion *et al.* [28] have carried out a fly's eye survey for transients which allowed them to survey 150 square degrees for 450 h and place interesting limits on bright, short duration bursts. Also with the ATA, there have been surveys for longer-duration transients [29], showing the power of arrays of small dishes. The V-FASTR project shows the value of commensal observing in which they piggyback on observations with the Very Long Baseline Array, which provides sensitivity, or rate limits, that are comparable, for some source classes, to the aforementioned surveys with Arecibo and the ATA [30].

Surveys using the all-sky monitor mode of LOFAR and beam formed modes began in 2012 and will be sensitive to transients in the frequency range 30–200 MHz [8,31]. The combination of the sophisticated and powerful LOFAR computing platform, the low observing frequency and the dipole-like receiving elements means that these surveys will revolutionize our understanding of the transient radio sky. The other SKA precursor telescopes such as ASKAP and MeerKAT also have planned transient programmes: VAST [32], CRAFT, TRAPUM and ThunderKAT [13], and these will all help pave the way for transient searches with the SKA in both phases. In addition to these new observing projects, there are exciting new developments in detection methods such as multi-moment analysis [33], the Chirpolator and Chimageator [34], millisecond imaging [35] and the use of interferometric closure quantities [36]. Significant developments are also being made in the use of new computing platforms such as graphics processing units [37,38].

5. Conclusions

The SKA will be a premier instrument for transient science, and the strength of the science case is only growing. This will continue as the current surveys identify new source classes. There is much development going on in hardware, software, simulation and data analysis techniques, all to improve the chances of detecting transients. All of the next generation telescopes are including the transient science case as one of the core goals, and this is also being reflected in developments at nearly all other wavelengths. With this rapidly developing and growing field, this article provides just a snapshot of the current status. We are currently honing the requirements for the SKA phase. This includes a strong case for taking advantage of the wide field of view of the upper half of the low-frequency sparse aperture array elements to search for transients. The complementary nature of the two dish arrays that will make up phase 1 will also provide the ability to carry out surveys which can be optimized for volume and area. The aperture arrays that may form part of the full SKA, and will operate in the mid-frequency range, will be the ideal receptor for searching for transients. One thing that remains a challenge is to maintain flexibility, particularly in the signal-processing regime, in the SKA system. It adds expense, but it will also ensure longevity.

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