Transient phenomena

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Abstract. The SKA’s design is driven by the needs of cutting-edge radio astronomy for sensitivity and spatial resolution. However its design is also driven by the desire to explore the transient radio Universe. In addition to pulsars, the SKA will be able to carry out high time resolution observations of several classes of known and predicted transient sources. Here we consider a selection of them, and describe how observational demands affect the instrument’s design.

1. Introduction

Two of the most famous examples of serendipity in astronomy resulted from chance observations of transient phenomena. Gamma ray bursts were first identified in the late 1960s and early 70s by the Vela satellite system, launched to verify Soviet adherence to the nuclear test ban treaty (Klebesadel et al. 1973), and at about the same time a Cambridge radio telescope designed for interplanetary scintillation studies resulted in the discovery of pulsars (Hewish et al. 1968). By definition, serendipity is not something one can rely on, but both these examples were a result of observations that explored a region of the spectrum with unprecedented sensitivity and time resolution. These are fundamental features of the SKA design, and we can certainly hope it will deliver something equally unexpected. However, we can see already that our understanding of many well-known transient sources will be enormously improved by SKA data. In addition to good sensitivity and time resolution, the SKA will offer the ability to carry out agile, event driven, observations and regular all-sky surveys – a feature normally associated only with low-frequency instruments.

It will be possible to map the structural evolution of transient sources with the SKA (a MERLIN example is considered in Section 2.3) but the simple rule we apply to signals of duration $\tau$ is that they cannot originate from a source larger than $\sim c\tau$. Although one can imagine pathological coherent emission propagation processes that would beat this rule, it it fair to say that the mapping of very short timescale sources will not be possible with the SKA. However astrometry will be possible, and has a particular significance for transient sources. For some classes of source we may have just a few seconds to determine the arrival direction, and suitable observing programmes for such sources will be discussed later in this review.
There are two important limiting processes that we should also keep in mind when considering transient sources. First, interstellar scattering becomes increasingly important at low frequencies and the temporal broadening of transients, effectively caused by multipath propagation through the turbulent interstellar medium, scales as $\sim \lambda^4$ (e.g., Cordes 1990). Very roughly we would expect a distant galactic or extragalactic transient to be broadened by $\sim 200 \mu s$ at 1 GHz and therefore 2 s at 100 MHz, although there is significant variation along different lines-of-sight. Second, because very short duration sources are necessarily small, they are likely to be self-absorbed at low frequencies. Both these effects favour higher frequencies for galactic and extragalactic transient observations.

2. Known transient radio sources

Even excluding pulsars (see Kramer in these proceedings) there is a remarkably broad range of known or predicted transient sources and phenomena that have received attention as suitable targets for SKA science. A brief, and incomplete, list of these includes

- solar system and extrasolar planetary emission (mostly at low frequencies, see Farrell et al. 1999),
- solar bursts (Bastian et al. 1998),
- interstellar and interplanetary radio propagation and space weather (Lazio 1999; Hick et al. 1996),
- microlensing events (Koopmans and de Bruyn, 1999 and 2000),
- air-shower events – radio pulses from cosmic rays hitting the Earth’s atmosphere (Horneffer et al. 2002),
- compact object coalescences (‘LIGO events’ – Usov and Katz 2000; Hansen and Lyutikov 2001),
- X-ray binary transients (Fender 1999),
- gamma ray burst transients and afterglows (Galama and de Bruyn, 1999; Dado et al. 2003),
- SETI (Welch and Dreher 2000).

A review of all these is not possible here, and details of each are available from the references cited and more general SKA documentation such as the SKA Working Group 2 Report on transient phenomena (Lazio et al. 2002). However we will consider three examples in more detail below to highlight the broad range of phenomena that come under the heading ‘transients’.
2.1. Solar imaging

The SKA will deliver the sub-arcsec resolution, millisecond sampling and frequency agility necessary to carry out imaging and 3-D tomographic modelling of the solar corona. These are techniques currently under development for the proposed Frequency-Agile Solar Radiotelescope or FASR (Bastian et al. 1998). FASR is a \( \sim 100 \)-antenna multi-frequency imaging array (\( \sim 0.1 \) to 30 GHz) with high spectral (\( \Delta f/f \sim 0.02 \)) and temporal (< 1 s) resolution. The SKA will be able to go even further, investigating the energy release mechanisms in the corona and the formation and destabilisation of large-scale structures in active regions and coronal loops. Current techniques, using instruments such as the Nobeyama radioheliograph at 17 GHz and the VLA at 5 GHz have begun to reveal the dynamics of plasma heating and electron acceleration within the corona on timescales as short as 0.1 s (e.g., Gopalswamy 1996; Zhang et al. 2001).

2.2. Microlensing

At first sight radio microlensing seems improbable, as most extragalactic radio sources are too extended to be strongly microlensed. However the compact features in the jet components of radiogalaxies are sufficiently compact (\( \mu \)parsec) to show microlensing and bright (\( \mu \)Jy to mJy) to be detected by the SKA in a matter of minutes (Koopmans & de Bruyn 1999). These microlensing transients will occur on timescales of days to weeks and should be distinguishable from refractive interstellar scintillation by their different spectral signatures. A particularly attractive feature of this technique is that, if the compact feature is superluminal, the microlensing rate could be as much as a thousand times greater than that from a stationary optical source. Koopmans & de Bruyn (2000) argue that the radio gravitational lens CLASS B1600+434 shows radio variability consistent with microlensing by massive compact objects in the bulge/disk and halo of the lens galaxy at \( z = 0.4 \). The SKA will offer the opportunity for more systematic studies of radio microlensing to measure the mass function of, and mass distribution in, high redshift galaxies and investigate the distribution of dark matter in galaxies as a function of redshift.

2.3. X-ray binary transients

X-ray binary systems, comprising an accreting neutron star or black hole with a donor stellar companion, represent one of the more accessible classes of exotic sources available to us, and have received much attention in recent years. As well as radiating in X-rays and gamma rays these sources can show highly variable radio emission together with radio jets. In addition low-mass X-ray binaries are thought to be relatively strong emitters of gravitational waves. The transient radio emission from these objects is often dramatic, and has been followed at many wavelengths (e.g., Brocksopp et al. 2002). Typically they comprise a rapid rise in flux, on timescales of hours and resolved images show rapidly evolving superluminal radio jets. A particularly spectacular example was seen in GRS 1915+105 by Fender et al. (1999) using MERLIN (Fig. 1).

The sensitivity and mapping capability of the SKA will allow the production of high resolution snapshot images of the evolving radio jets in these sources. With sensitivities in the \( \mu \)Jy range observations can be extended to the extragalactic population of X-ray binaries in the Local Group (Fender 1999). The
Figure 1. Radio evolution of the X-ray transient source GRS 1915+104 at 5 GHz (from Fender et al. 1999). These are MERLIN maps of total intensity.
mechanism for the radio jets and the relationship between the X-ray and radio emission remain unclear, and the SKA will revolutionise the study of this class of transient source.

3. Observing programmes and requirements

The SKA transient programme has a broad remit, and the observational demands it makes have significant consequences for the design of the telescope. Sufficient time resolution is obviously essential and is common to both the pulsar and transient programmes. The most stringent constraints for this are from solar imaging, for which the SKA should be able to deliver snapshot images of coronal features on timescale of milliseconds.

Transient observations will sometimes be triggered by observations from other instruments. For GRBs we have some dispersive delay between the gamma ray and radio signals, relaxing the response time requirements slightly, but there will be other situations when transient observations are totally missed in real-time. To recover the data would need a ‘delay buffer’ in the SKA design, capable of retrospective beam forming and synthesis. Implementing such a buffer might be difficult, but would greatly enhance the SKA’s transient performance. In addition to follow-up and triggered response observations the SKA will be configured to perform directed searches for transients, such as from X-ray binaries or from extreme scattering events (Fiedler et al. 1987). In addition, an efficient SETI monitoring programme can be developed by synthesising multiple beams directed at local stars. The multiple beam-forming capabilities of the SKA can also be exploited to carry out the first systematic all-sky transient surveys, using sub-arrays to survey different parts of the sky and distinguish between RFI and true transients (Lazio at al. 2002).

These transient programmes will span the full frequency range of the strawman design (150 MHz to 15 GHz). The low frequency end will be particularly important in planetary observations, galactic and extragalactic giant pulse observations in the pulsar transient programme and possibly for follow-up observations from future gravitational wave inspiral detections. Higher frequency observations are less affected by self-absorption and angular and temporal broadening by the ISM, particularly towards the galactic centre. The field-of-view (FoV) requirements are also stringent if the whole sky is to be covered in a reasonable length of time. A full-sky survey taking 1 day, with a 1 square degree FoV leaves only 5 s of integration per pointing. The astrometry requirements for transients are also demanding, with 1 to 10 mas resolution at 5 GHz desirable if the SKA is to compliment ALMA and the NGST.

The SKA promises to be a remarkable instrument, and all those involved with its conception are keen to explain how it will revolutionise our existing understanding of the radio Universe. However its most lasting contribution may well be in the unexpected, previously unimagined, areas of astrophysics that it will reveal. The transient programme in particular covers volumes of parameter space in sensitivity and time resolution that are far in excess of anything that has been available before, and we await its exploration with much excitement.
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