Radio transients: an antediluvian review

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Abstract. We are at the dawn of a new golden age for radio astronomy, with a new generation of facilities under construction and the global community focused on the Square Kilometre Array as its goal for the next decade. These new facilities offer orders of magnitude improvements in survey speed compared to existing radio telescopes and arrays. Furthermore, the study of transient and variable radio sources, and what they can tell us about the extremes of astrophysics as well as the state of the diffuse intervening media, have been embraced as key science projects for these new facilities. In this paper we review the studies of the populations of radio transients made to date, largely based upon archival surveys. Many of these radio transients and variables have been found in the image plane, and their astrophysical origin remains unclear. We take this population and combine it with sensitivity estimates for the next generation arrays to demonstrate that in the coming decade we may find ourselves detecting 10^5 image plane radio transients per year, providing a vast and rich field of research and an almost limitless set of targets for multi-wavelength follow up.

Keywords : surveys – telescopes – transients – methods: observational – radio continuum: general – techniques: miscellaneous

1. Radio transients: the potential

The Universe is a violent and dynamic environment, in which the explosions of massive stars can outshine an entire galaxy, supermassive black holes swallow stars whole, merging neutron stars cause ripples in the fabric of spacetime and bursts of ultra-high energy radiation which can be detected at vast distances, and particles are accelerated to energies far surpassing anything possible in laboratories on the Earth. The extremes of physics – density, temperature, pressure, velocity,

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gravitational and magnetic fields – experienced in these environments provide a unique glimpse at the laws of physics operating in extraordinary regimes. Such 'extreme astrophysics', is a high priority for global research in the 21st century[1]. In the second half of the 20th century, astronomy moved beyond its optical origins into the radio, infrared, ultraviolet, X-ray and gamma-ray bands. The most extreme environments in the Universe betray themselves by their copious high-energy emission, in the X-ray and gamma-ray bands, and also by their radio emission. Strong magnetic fields and shock waves as matter collides in the ambient medium, result in radio bursts from electrons (and positrons) spiralling around, and sometimes being channelled along, these magnetic field lines. Wide-field orbiting X- and gamma-ray observatories, with all-sky monitors, have revealed our Galaxy to be a hotbed of explosive and relativistic effects, which go largely unnoticed by traditional optical telescopes both because they are missed in the narrow fields of view, and are obscured by interstellar dust. By far the best way to observe and understand the violent Universe from the ground is via the radio emission which is ubiquitously associated with these violent events. The emission arises as the shocked particles glow with synchrotron radiation, streaming along and around magnetic field lines, or are induced to move and emit coherently, producing extremely bright bursts. However, in the past radio astronomy, like optical astronomy, has suffered from the narrow fields of view which are a consequence of large dishes, and cannot survey the sky sufficiently rapidly to detect rare and rapid events, which may be the most significant astrophysically. All of this is about to change, with a new generation of radio telescopes, taking advantage of new technology and the vast advances made in data transport and computer processing, connecting large numbers of small detectors, able to deliver enormous fields of view. Finally the age of the radio all-sky monitors is here. What is more, these radio all-sky monitors will have several advantages over the traditional X-ray and gamma-ray monitors: they will be able to localise events immediately with arcsec precision, and will be able to go significantly deeper / further.

As we shall demonstrate in this review, our current understanding of the population of radio transients implies that we should detect thousands, or even millions, of such events with 'next generation' radio facilities such as The Low-Frequency Array (LOFAR), The South African Karoo Array Telescope (MeerKAT) and The Australian SKA Pathfinder (ASKAP), and ultimately the Square Kilometre Array (SKA). As well as drawing our attention to the extremes of astrophysics, these sources are potentially observable to vast distances (possibly as far as the Epoch of Reionisation at redshift $z > 6$) and will turn out to be amongst our most valuable probes of the intergalactic and intercluster medium on large scales. They may furthermore, in some cases, turn out to be the electromagnetic signatures of events which produce detectable gravitational waves, which would be a breakthrough connection.

2. Transient and variable source populations

In the following subsections, we shall briefly discuss the diverse populations of transient and variable radio sources, which we separate into incoherent and coherent processes. These two

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[1]See e.g. the ASTRONET report *A Science Vision for European Astronomy* available at **www.astronet-eu.org**

source populations also divide, roughly, in the technique which is optimised for their discovery: incoherent synchrotron transients will be mostly discovered and studied in the image plane, and coherent sources in time series analyses using in large part the methods traditionally used for radio pulsars. There is, it should be noted, some considerable overlap between the two, in particular as many coherent sources are likely to be strong, long-lasting and/or dispersed enough to be detectable in images. The incoherent sources are also referred to, somewhat disparagingly, as 'slow' transients, and the coherent sources as 'fast' (Cordes 2007).

2.1 Synchrotron sources

All astrophysical events which are associated with the explosive injection of energy into an ambient medium result in synchrotron emission. The explosive event creates shocks which accelerate particles to extremely high energies (sometimes above 10^{19} eV), as well as compressing and amplifying the ambient magnetic field. The accelerated ultrarelativistic particles spiral around the magnetic field lines, emitting polarised synchrotron radiation as they lose energy (see e.g. Longair 1994). A wide variety of astrophysical phenomena are associated with synchrotron emission, including a menagerie of explosive events such as:

- supernovae resulting from the collapse of the iron core of a massive star, or the conflagration of an entire white dwarf as it reaches the Chandrasekhar limit (Weiler et al. 2002);

- giant outburst from magnetars, powered by the rearrangement of the magnetic field of super highly-magnetised neutron stars (Gaensler et al. 2005);

- classical nova explosions, caused by a wave of nuclear fusion across the entire surface of a white dwarf (e.g. Pavelin et al. 1993);

- relativistic jets (Hughes 1991), powerful outflows of kinetic energy and matter launched from the cores of accreting black hole and neutron star systems (e.g. Fender 2006); this phenomenon, which is vital to black hole accretion and feedback, is as yet poorly understood and yet seen across a broad range of objects from stellar-mass to supermassive black holes, and even gamma-ray bursts (e.g. Frail et al. 2003), the most powerful explosions in the Universe.

Fig. 1 illustrates an incoherent synchrotron outburst from a Galactic binary source. The lower (< 1 GHz) frequencies peak lower and later than the higher (GHz) frequencies, due to evolving source size and optical depth. Note that the duration of such events depends upon the rate at which their volume changes significantly. For similar (relativistic or mildly relativistic) expansion velocities, this means that less luminous events (e.g. flares from cataclysmic variables or X-ray binaries (such as that in Fig. 1) will evolve much more rapidly than more luminous events such as SNe, GRB afterglows and AGN outbursts (which can of course be seen to much larger distances). It is also worth noting, although it is obvious, that the decay phase lasts much longer than the rise phase (even at MHz frequencies), and so the radio sky may turn out to be
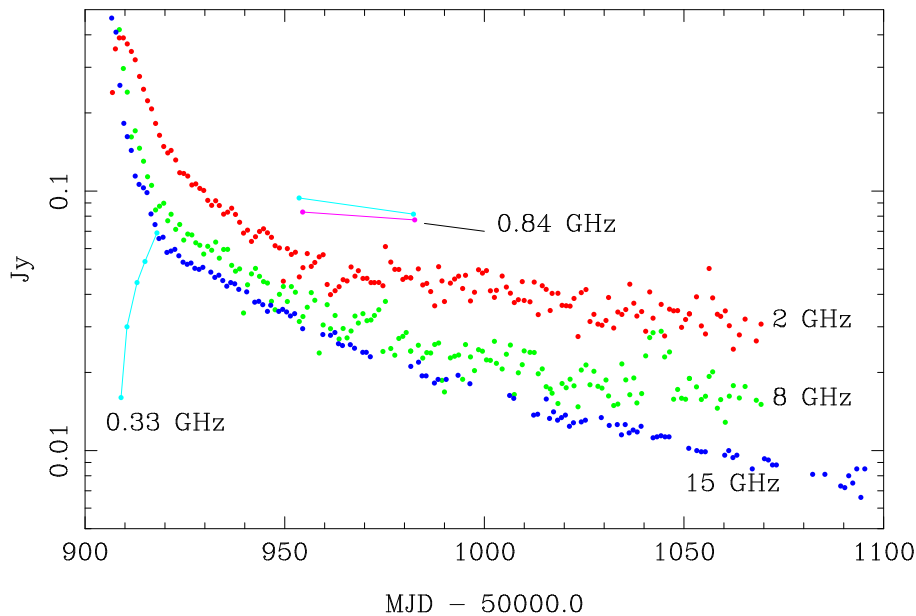
Figure 1. An outburst of the binary transient CI Cam observed at radio wavelengths. This is incoherent synchrotron emission from electrons shock-accelerated by the ejection of matter from the binary system (in a jet and/or wind). The initial rise phase corresponds to a combination of the particle acceleration timescale (which may dominate at high frequencies) and the evolution of initially self-absorbed emission to optically thin (which clearly dominates below 1 GHz).

dominated by faint sources which are slowly fading (e.g. thousands of fading GRB afterglows across the sky).

2.2 Coherent bursts

Short-timescale (often less than one second, sometimes unresolved on millisecond timescales) 'coherent' transients are also often associated with some of the highest energy density events in the Universe. However, unlike synchrotron radiation, which in a steady state is limited to a brightness temperature of $\sim 10^{12}$ K, for the most extreme coherent events the brightness temperature is in excess of 10^{35} K. Pulsar emission is perhaps the most famous form of coherent radio emission, and has unequivocally demonstrated its astrophysical importance by demonstrating the existence of neutron stars (Hewish et al. 1968, leading to the Nobel Prize 1974) and providing exquisitely precise tests of general relativity (Hulse & Taylor 1975, leading to the Nobel Prize, 1993). The same coherent emission is also associated with other relatives of the standard radio pulsars, such as the RRATs and intermittent pulsars (McLaughlin et al. 2006).

In 2007, Lorimer et al. (2007) announced the possible discovery of a short duration, dispersed
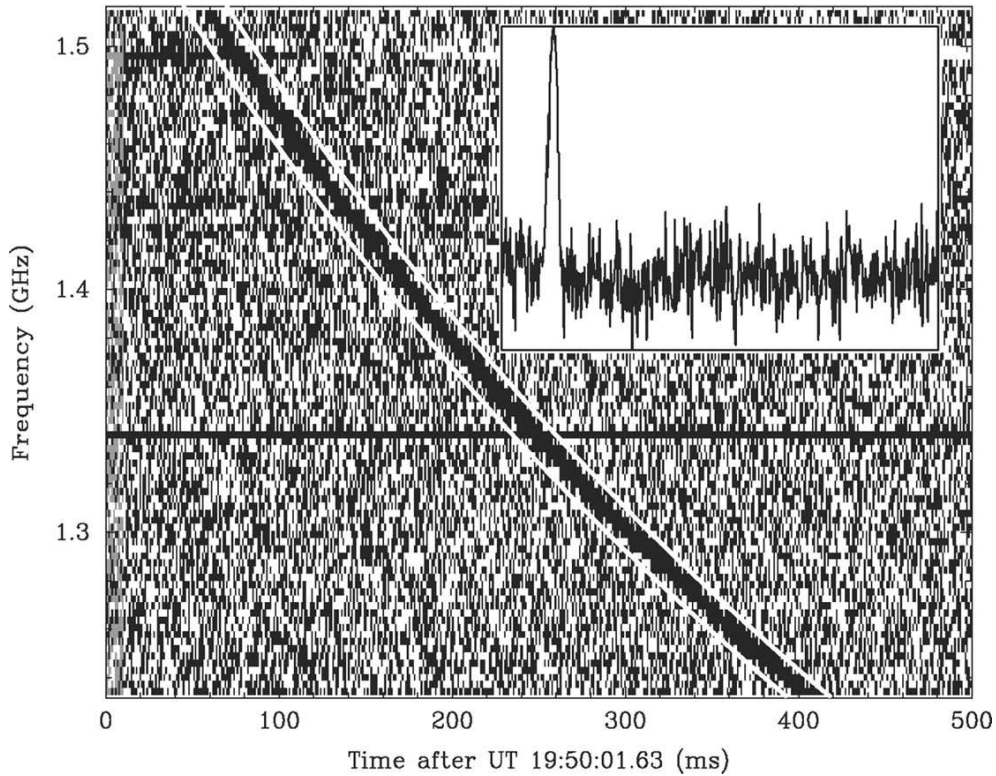
Figure 2. The observation of a possible coherent radio burst at a distance of ~500 Mpc (Lorimer et al. 2007), showing the quadratic dispersion signature expected for an event of astrophysical origin (but see Burke-Spoloar et al. 2011 and Keane et al. 2011). Such bursts could potentially be seen as far back as the first population of luminous objects in the epoch of reionisation, and could be unparalleled tools for the study of the intergalactic and intercluster medium on the largest scales. Reprinted with permission from AAS.

burst from an estimated distance of 500 Mpc (Fig. 2). They furthermore estimated that there should be hundreds of such bursts per day across the sky. Although there remains some doubt as to the astrophysical origin of the burst (Burke-Spoloar et al. 2011, but see Keane et al. 2011 for other possible events), such bursts would open up an entirely new field of astrophysics, acting as probes of the intergalactic medium (IGM) by measuring pulse dispersion and broadening, providing direct measures of the IGM magnetic field and turbulence.

For the rest of this review we shall focus on current best estimates of the radio transients population, and how it maps onto the sensitivities of the new generation of radio facilities. Nearly all of this work is done in the image plane and corresponds to 'slow' transients. For much more on fast transients we refer the reader to e.g. Cordes, Lazio & McLaughlin (2004), Cordes (2007), Hessels et al. (2009), Stappers et al. (2011), Keane & McLaughlin (2011).

3.   The current situation

Despite the scientific potential, the transient and time variable radio sky is a relatively unexplored region of parameter space. The restricted survey speeds of older generation radio facilities has meant that detections of radio transients lag far behind that which is possible with, for example, X- and gamma-ray instruments. Four dominant methods have so far been used to detect radio transients (i) dedicated surveys (ii) multi-wavelength triggered detections (iii) archival studies and (iv) serendipitous and commensal detections. Commensal refers to the process of searching numerous wide field or deep observations, which have been obtained to address a number of scientific goals. Commensal observations can provide many thousand of hours of data without interrupting an over subscribed telescope schedule (discussed and quantified further later). Some radio transients have been detected serendipitously over the years, but they so far remain relatively limited in number (for examples see Davies et al. 1976; Zhao et al. 1992; van den Oord & de Bruyn 1994; Bower et al. 2003 and Lenc et al. 2008).

3.1   Dedicated surveys

The first well-studied variables in the mid to late 20th century were typically bright (often 3C) extragalactic radio sources (for examples see Hunstead 1972; Condon & Backer 1975; Ryle et al. 1978; Condon et al. 1979; Dennison et al. 1981; Taylor & Gregory 1983; Aller et al. 1985; Simonetti & Cordes 1990; Riley 1993; Lovell et al. 2008). The focus at that time was primarily placed on studying the intrinsic properties (including scintillation) of these known sources, rather than exploring parameter space. Some of the papers above often refer to the fractional change (including alternative metrics of variability) in the flux of a source on a specific timescale, rather than the number of sources (per $\deg^2$) whose flux changed by a given amount on a specific timescale. The latter is more useful for understanding the global population i.e. the number of sources which are extremely variable in a given flux and time interval, per solid angle on the sky.

As well as distant extragalactic radio sources, more recently nearby galaxies have been common targets for transient surveys. For example, M82 hosts a large number of supernovae remants due to a prolific star formation rate; a number of unidentified radio transients have also been detected (Kronberg & Sramek 1985; Muxlow et al. 1994; Brunthaler et al. 2009; Joseph, Maccarone & Fender 2011). The Galactic centre has also been the area for some intense observing campaigns. These surveys have so far detected a number of radio transients (Davies et al. 1976; Hyman et al. 2002; Bower et al. 2005; Hyman et al. 2006, 2007, 2009).

In recent years the focus has also shifted towards performing (truly) dedicated blind surveys of parameter space to search for radio transients (i.e. not necessarily targeting hotbeds of nearby transient activity). These surveys have also focused on parameterising the rate of events on the sky (a discussion of which will follow later). For example, nine bursts – named the WJN transients – in excess of 1 Jy have been reported from drift scan observations with the Waseda Nasu Pulsar Observatory at 1.4 GHz, which are summarised in Matsumura et al. (2009) (also see Kuniyoshi et al. 2007; Niinuma et al. 2007; Kida et al. 2008; Niinuma et al. 2009 for further details). These

are some of the brightest slow transients (lasting minutes to days) which have been reported in the literature: they so far remain unexplained. Croft et al. (2010) published results from the dedicated Allen Telescope Array Twenty Centimetre Survey (ATATS): no unique transients were detected and an upper limit on the snapshot rate of events was given. A follow-up paper by Croft et al. (2011) further constrained the rates of radio transients; both papers also present a comprehensive study of the variability of persistent sources within the observations. Subsequently the Pi GHz Sky Survey (PiGSS) surveyed the sky with the ATA at 3.1 GHz, providing the deepest static source catalogue to date above 1.4 GHz (Bower et al. 2010). No unique radio transient sources were reported in this survey and an upper limit on snapshot rate was placed (also see Bower et al. 2011). In the low frequency regime Lazio et al. (2010) have used the Long Wavelength Demonstrator Array (LWDA) at 73.8 MHz to perform an all-sky survey for bright ($>$ 500 Jy) moderately fast ($\sim$ 5 minutes) transients. No astronomical sources are detected which places a stringent limit on the rate of extremely bright ($\geq$ 500 Jy) low frequency events.

In conjunction with searching for unique (previously unknown) transient radio sources, searching for highly variable faint radio sources can also be a useful diagnostic in examining the dynamic radio sky. For example, Carilli, Ivison & Frail (2003) found a number of highly variable ($\Delta S \geq \pm 50\%$) radio sources in a small number of repeated observations of the Lockman Hole at 1.4 GHz. Frail et al. (2003) found four highly variable radio transient sources from follow-up observations of GRBs at 5 and 8.5 GHz. Reporting 39 variable radio sources, Becker et al. (2010) characterised the surface density of variables in the direction of the Galactic plane at 4.8 GHz. The majority of the variable sources presented in Becker et al. (2010) had no known multi-wavelength counterparts. Ofek et al. (2011) also perform a blind search for transients at low Galactic latitudes. This study is one of the first to characterise the variability of sources on pre-described cadences (days, months and years).

3.2   Multi-wavelength triggered detections

Since the development of high energy observatories detections of radio transients have often relied on multi-wavelength triggered observations. These have produced radio counterparts to gamma-ray burst (GRB) afterglows, Soft Gamma-Ray Repeaters (SGRs) and extremely rich datasets of black hole X-ray binary outbursts (for examples see Frail et al. 1997; Eck, Cowan & Branch 2002; Gaensler et al. 2005; Fender, Homan & Belloni 2009). This method relies on having a detectable high frequency counterpart, which may be absent (or difficult to detect) for sources such as X-ray dim isolated neutron stars (XDINs; see Ofek et al. 2009 for a discussion) and orphan gamma-ray burst afterglows (Frail et al. 1997).

3.3   Archival studies

Radio telescope archives potentially contain many hours of data which currently remains to be searched for radio transients. An archival study comparing the NVSS (NRAO VLA Sky Survey; Condon et al. 1998) and FIRST (Faint Images of the Radio Sky at Twenty-cm; Becker, White

& Helfand 1995; White et al. 1997) catalogues was conducted by Levinson et al. (2002) to constrain the rates of orphaned GRB afterglows. A follow-up study was conducted by Gal-Yam et al. (2006) and a number of radio transient sources were identified. Thyagarajan et al. (2011) have recently performed the most thorough analysis of the FIRST survey to date, reporting 1627 transient and variable sources down to mJy levels, over timescales of minutes to years. Thyagarajan et al. (2011) report that – so far – 877 of the detected variable sources lack optical counterparts. See also de Vries et al. (2004) and Ofek & Frail (2011) for further analysis and discussion of the FIRST and NVSS catalogues.

In what remains the benchmark study, Bower et al. (2007) analysed 944 epochs of archival VLA data at 4.8 and 8.4 GHz spanning a period of 22 years. In this survey ten radio transients were reported, with the host galaxies possibly identified for four out of the ten sources, and the hosts and progenitors of the other six unknown. Croft et al. (2011) perform X-ray follow-up of the transient sources reported in Bower et al. (2007), from which eight sources still remain completely undetected. Bannister et al. (2011) published results from a search for transient and variable sources in the Molonglo Observatory Synthesis Telescope (MOST) archive at 843 MHz: 15 transient and 53 highly variable sources were detected over a 22 year period. Bannister et al. (2011) use these detections to place limits on the rates of transient and variable sources. Bower & Saul (2011) and Bell at al. (2011) have published further archival work examining observations of the VLA calibrator fields. The calibrators are the most heavily observed VLA fields and are rarely imaged for scientific purposes. Both these studies placed constraints on the rates of transients at GHz frequencies and each study analysed thousands of images respectively. Also, Gaensler & Hunstead (2000) examined archival observations of the Molonglo calibrators reporting that 18 out of 55 were variable on timescales one to ten years.

The NVSS, FIRST (and other legacy surveys) are extremely important for transient studies because they offer a comparative catalogue to assess the flux density, timescale and robustness of new transient and variable sources. Two new all-sky legacy surveys are planned (EMU – Evolutionary Map of the Universe and WODAN – Westerbork Observations of the Deep APER-TIF Northern-Sky) which will produce both Northern and Southern hemisphere catalogues down to micro-Janksy sensitivities: these will provide the bedrock for new transient and variability studies. These new surveys can also be compared with older legacy surveys such as NVSS and SUMSS (Sydney University Molonglo Sky Survey; Bock et al. 1999) to search for further transient sources.

Archival studies are hampered by the inability to perform instantaneous real time follow-up, which is often needed to correctly classify a source. So far, a large fraction of the reported transients appear to lack optical and X-ray counterparts (Bower et al. 2007; Matsumura et al. 2009; Thyagarajan et al. 2011), either the sample of sources so far are indeed optically and X-ray dim (Ofek et al. 2010), or this is selection effect related to the time between follow-up. The current state-of-the-art $\log N$–$\log S$ for GHz transients, from Bower et al. (2011), is presented in Fig. 3.
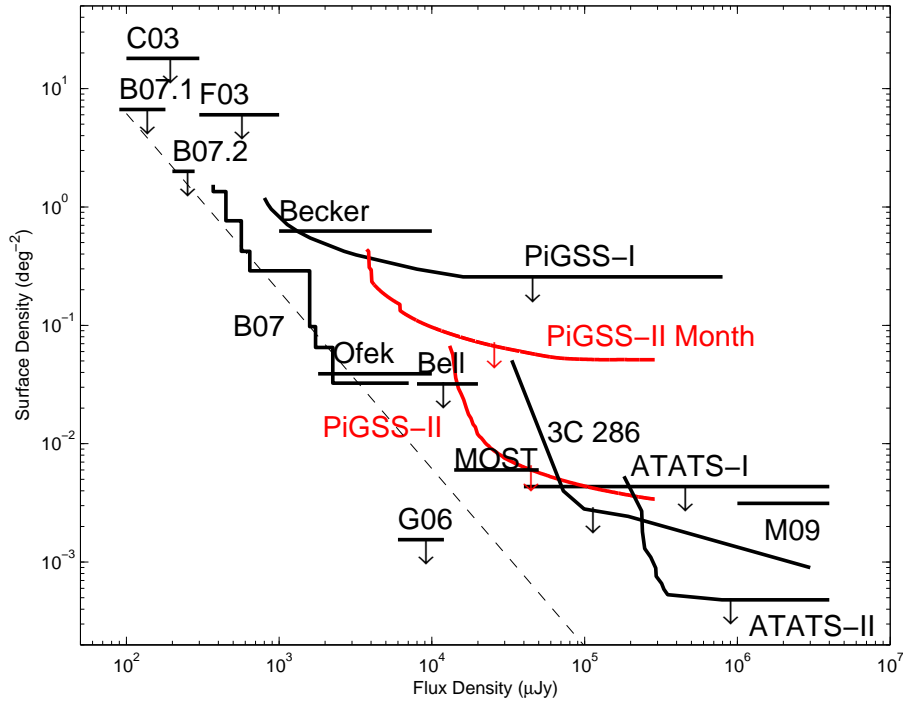
Figure 3. The current state of the art $\log N - \log S$ distribution for GHz-frequency radio transients with variability timescales of weeks (from Bower et al. 2011). While most surveys have resulted in limits on source populations, the definitive study remains that of Bower et al. (2007), for which the slope of the population (indicated by 'B07' in the figure) is consistent with a homogenous source population in Euclidean space. Fig. 5 extends this figure to include the MHz results of Lazio et al. (2010) and demonstrates how, based upon the Bower population, the next-generation facilities should discover very large numbers of such sources. Reproduced by permission of the AAS.

4. The future

Radio astronomy appears to be at the dawn of a new golden age, with major facilities under construction and older facilities undergoing dramatic upgrades, driven in large part by the desire to achieve the full Square Kilometre Array within 15 years (e.g. Carilli & Rawlings 2004).

In some cases, these new facilities and upgrades are already here, and their potential just starting to be explored. In the following section we discuss how, based upon the existing population studies, we expect the new radio telescopes to perform as transient detection machines.

4.1 Estimated transient detection rates

For a homogenous set of sources distributed in Euclidean space, we expect the number of detected sources N per steradian (i.e. the surface density) to be a function of sensitivity S (smaller S is more sensitive) such that $N \propto S^{-3/2}$ which is consistent with the results found in Bower et al. (2007). We can take this assumption and use it to compare the expected potential for transient population studies with different telescopes, if we take into account their fields of view, Ω i.e. $N \propto \Omega S^{-3/2}$, which means that on a plot of sensitivity against field of view, functions of the form $S \propto \Omega^{2/3}$ correspond to constant numbers of transients (or, indeed, sources of any kind) found. This function is useful for comparing estimated transient rates in simple observations (often performed for other scientific goals). We present such a plot, with lines drawn indicating constant numbers of transients, for the next generation radio facilities, together with a subset of major existing facilities, in Fig. 4. Of course such estimates are very crude, taking no account of a heterogenous source population nor observing strategy.

Note that this measure of sources found differs slightly from the traditional radio telescope survey figure of merit (FOM), which corresponds to the number of square degrees per unit time that can be surveyed to a given flux limit: FOM$\propto \Omega/\delta t \propto \Omega S^{-2}$ (since the sensitivity achieved in a given integration time δt is $\propto \delta t^{-1/2}$). This leads to functions for a constant FOM, on the same figure, of the form: $S \propto \Omega^{1/2}$. Both functions are indicators of the potential for the exploration of discovery space with different facilities.

It is clear from Fig. 4 that the new / upgraded generation of GHz facilities (EVLA, MeerKAT, WSRT-APERTIF and ASKAP) could each – under the naive assumptions made above – discover comparable number of transient sources. Viewed this way, the low frequency array LOFAR does not appear competitive. However, it is important to correct for the order of magnitude frequency difference between the GHz facilities and LOFAR. A typical synchrotron source at low radio frequencies, once optically thin, would have a spectral index $-0.5 \geq \alpha \geq -1.0$ where $S_\nu \propto \nu^\alpha$. For $\alpha \sim -0.7$, LOFAR is comparable to the ATA; for $\alpha \sim -2$, LOFAR is arguably the best facility (these corrected figures are indicated in Fig. 4 by the open symbols). Although $\alpha \sim -2$ is steep for a synchrotron source, it is not at all unusual, and arguably rather shallow, for a coherent source. This, then, demonstrates that LOFAR, while being a powerful instrument for synchrotron sources, will be the world-leading facility for coherent sources. This statement does of course depend rather heavily on the assumption that reasonable correction can be made for propagation effects (e.g. dispersion) which are stronger at lower frequencies. It may well transpire that the GHz and MHz facilities sample populations with quite different fractional contributions from synchrotron and coherent sources, and a comparison of the MHz transient population with the Bower et al. GHz distribution is one of the key early science goals for LOFAR.

We may look at predictions for the new radio facilities in more detail. Fig. 5 shows an adapted version of the flux density versus snapshot rate plot (see Fig. 3). In this figure we plot only the blind transient surveys which have detected transient or variable sources; for clarity we include the Lazio et al. (2010) upper limit. These come from the 73.8 MHz Long Wavelength Demonstrator Array, have the widest field of view of any survey to date, and are the benchmark
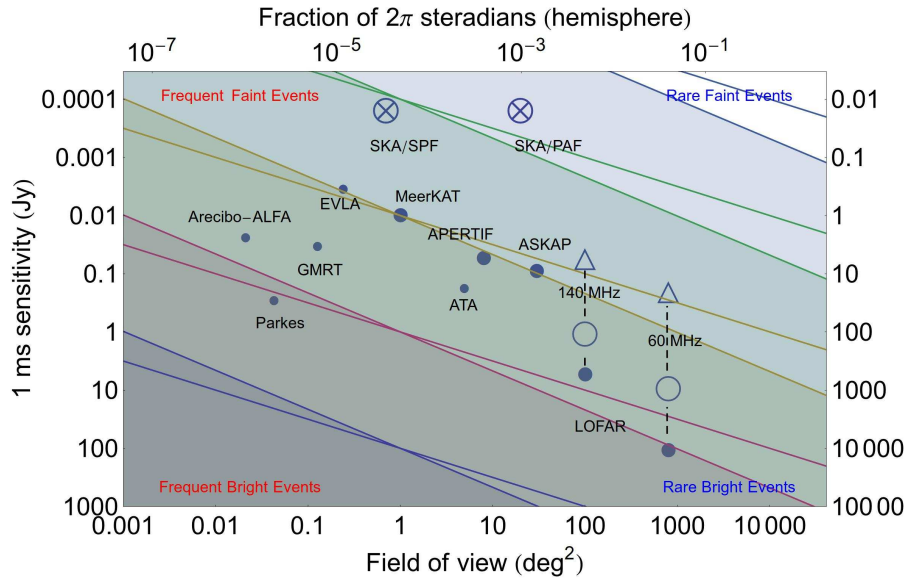
Figure 4. Illustration of the sensitivities and fields of view of some of the current and next generation of radio telescopes. For LOFAR which operates at much lower frequencies than the other facilities (which, for the purposes of this figure, we assume are all operated in the 1.4 GHz 'L' band), we show both the 140 MHz and 60 MHz bands, each with raw sensitivities and two sets of spectral connections (connected by the vertical dashed lines). The open circles represent a correction for a spectral index of −0.7, expected for optically thin synchrotron sources at low frequencies. The open triangle represents a lower limit on corrections for a population of coherent sources, which are likely to be at least as steep as spectral index −2. These scenarios are also reproduced in the source count estimates in Table 1. Also indicated are lines indicating a constant number of detected sources for a homogenous population of sources in a Euclidean Universe (FoV ∝ sensitivity$^{2/3}$) in a single observation, as well as the more traditional survey figure of merit, (FoV ∝ sensitivity$^{1/2}$) which corresponds to the number of square degrees per unit time to a uniform depth. These are indicators of likely yields from simple pointings and surveys, respectively. It is noteworthy that the new generation of GHz-frequency facilities (EVLA, MeerKAT, WSRT+APERTIF and ASKAP), despite having different combination of field of view and sensitivity, all have comparable survey speeds. This figure was inspired by Fig. 1 of Macquart et al. (2010).

against which the first wide-field LOFAR transient surveys will be measured (as noted before, the MHz and GHz populations of transients may be rather different). Also shown is the derived least-squares best fit to the Bower et al. (2007) detections of 1 week duration (thin black line).

In Fig. 5 the vertical dashed lines represent the r.m.s. noise (in a 12 hour observation) for a number of SKA pathfinder instruments. The corresponding horizontal lines represent the 2σ upper limit on the snapshot rate, derived from 10 epochs of data with each instrument respectively.
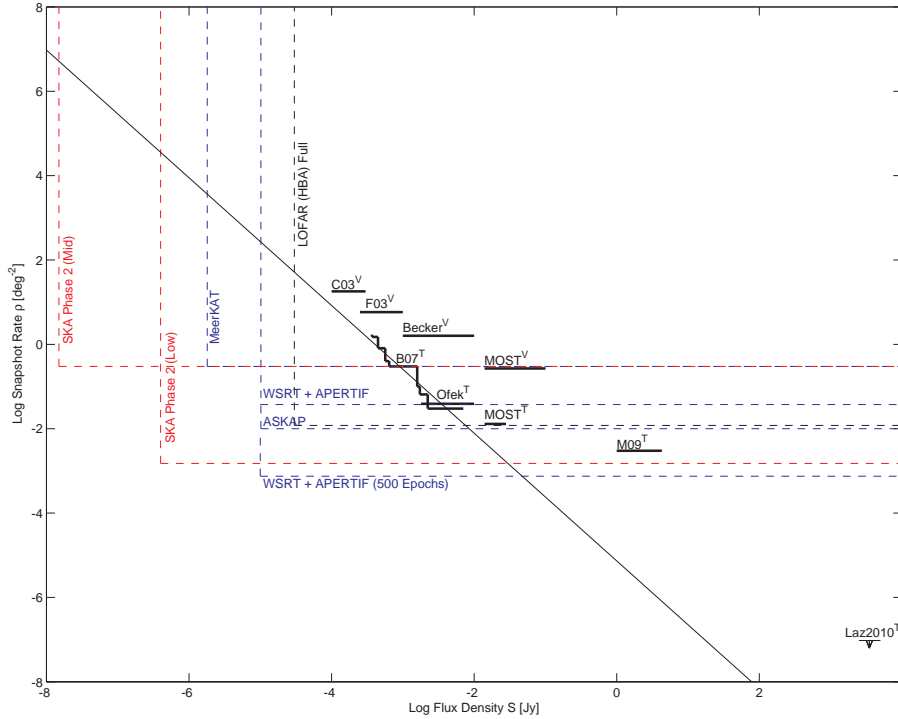
Figure 5. Log of the Snapshot rate (deg^{-2}) against log of the flux density (Jy) of detections of transients (labelled 'T'), detections of variable sources (labelled 'V') and upper limits based on non-detections (labelled with downward arrows). The dashed lines represent the sensitivity (vertical), and 2σ upper limits on the snapshot rate (horizontal), derived for a number of SKA pathfinder instruments, assuming zero detections in 10 epochs of data. It is clear that the new facilities will push deep into detection territory – see Table 1 for estimated rates.

For the SKA Phase 2 we adopt the values quoted in Carilli et al. (2003); for a frequency of 1.4 GHz, an r.m.s. of 37 nJy, and a Field of View (FoV) of 1 deg^2 is realised. For a frequency of 200 MHz (c.f. LOFAR), an r.m.s. of 0.4 μJy, and a FoV of ~200 deg^2 is realised. The Aperture Tile in Focus (APERTIF) upgrade to the Westerbork Synthesis Radio Telescope (WSRT) and the ASKAP telescope achieve a similar sensitivity of ~ 10 μJy (at 1.4 GHz) in a 12 hour observation, however ASKAP will image a FoV of 30 deg^2, compared to 8 deg^2 for APERTIF (see Oosterloo et al. 2010 and Johnston et al. 2007 for further details). The MeerKAT telescope is designed for high dynamic range imaging, and will achieve an r.m.s. of ~1.8 μJy in 12 hours, with a FoV of ~1 deg^2 at 1.4 GHz.

Fig. 5 also shows the potential full array sensitivity of LOFAR (31 μJy), assuming a 12 hour integration at 120 MHz and 10 repeat visits to the same field. A greater FoV can be achieved with LOFAR by using multiple beams to tile up a larger FoV, however, this comes with a trade

off of sensitivity. Assuming that the transient population detected by Bower et al. (2007) are in some way representative of the global population; by either improving the sensitivity (which pushes the detection limit on Fig. 5 to the left); *or* by imaging larger FoVs (which pushes the horizontal snapshot rate limit down), the transient population can be efficiently explored. Note, in Fig. 5 we do not correct for any spectral index effects, with respect to the GHz and MHz surveys and predictions. An order magnitude increase in flux from 1.4 GHz to 150 MHz would be expected for a source with $\alpha = -0.7$. This in turn would shift the $\log N - \log S$ of the Bower et al. (2007) GHz detections to the right. This is probably an over-simplification, however, it should be considered when plotting fluxes and snapshot rates derived at two different frequencies.

Taking the Bower et al. (2007) best fit and extrapolating to the SKA Phase 2 (Mid) sensitivity limit using:

$$\log \rho = -1.5 \log S_v - 5.13$$

Where ρ is the snapshot rate and S_v is the detection threshold of the observations. Assuming a 5σ detection is needed, an huge snapshot rate of 4.4×10^5 deg^{-2} is predicted for the SKA Phase 2 (Mid). We also summarise the predicted snapshot rates for other instruments in Table 1. The predictions are extremely speculative about the true nature of the transient population, however, even if the $\log N - \log S$ is less steep, large numbers of transient detections are still expected.

The examples above have assumed that only ten repeat visits are obtained of the same field. Using the proposed 1.4 GHz–band APERTIF surveys[2] as an example, we can calculate how many repeat visits we could expect from a commensal survey. The APERTIF surveys will last for a period of ~five years and will tackle a number of scientific goals. The proposed surveys fall into the following three categories:

- **Shallow**
  (1×12 hours) $\times$ 1250 fields.
  Total: 10,000 deg^2 revisited once.

- **Medium deep**
  (10×12 hours) $\times$ 125 fields.
  (12×12 hours) $\times$ 5 fields.
  Total: 1000 deg^2 revisited 10 times.

- **Deep**
  (100×12 hours) $\times$ 5 fields.
  Total: 40 deg^2 revisited 100 times.
  (500×12 hours) $\times$ 1 fields.
  Total: 8 deg^2 revisited 500 times.

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[2]http://www.astron.nl/radio-observatory/apertif-eoi-abstracts-and-contact-information

Table 1. Predicted rates of radio transients for SKA pathfinder instruments. The calculations are based on the $\log N - \log S$ of the Bower et al. (2007) detections at 4.8 GHz. The snapshot rate column shows the rate extrapolated to the 3σ detection limit of each instrument respectively (Note, per deg^2). The Bower et al. (2007) survey had a cadence of ~one week, therefore the rate per year column shows the expected rate of transients in 52 weeks of observing. Note, this is a lower limit because the characteristic timescale of the Bower et al. (2007) transients were between 20 minutes and one week, we also do not consider any recurrence in transient activity. The yield columns give the number of transients expected for each instrument over the intrument's FoV. The LOFAR rates do not take into account any spectral index considerations. Therefore, assuming a spectral index of $\alpha = -0.7$ (synchrotron) and $\alpha = -2$ (coherent) we show the corrected rates based on these spectral indexes. The coherent rates in particular should be taken with a lot of caution, since they depend on both what fraction of the Bower et al. population were coherent, and how well we will be able to deal with propagation and scattering effects at low radio frequencies.

Instrument	Snapshot rate (deg^{-2})	Rate per year ($deg^{-2}\ yr^{-1}$)	Yield (yr^{-1})
SKA Phase 2 (Mid)	9.7×10^5	5.0×10^7	5.0×10^7
SKA Phase 2 (Low)	6.7×10^3	3.5×10^5	7.0×10^7
MeerKAT	6.9×10^2	3.6×10^4	3.6×10^4
WSRT + APERTIF	5.0×10^1	2.6×10^3	2.0×10^4
ASKAP	5.0×10^1	2.6×10^3	7.8×10^4
LOFAR (HBA) Full	9.8	5.0×10^2	1.2×10^4
LOFAR (HBA) Full ($\alpha = -0.7$)	1.0×10^2	5.3×10^3	1.3×10^5
LOFAR (HBA) Full ($\alpha = -2$)	8.9×10^3	4.6×10^5	1.2×10^7
SKA Phase 2 (Low)($\alpha = -0.7$)	5.5×10^4	2.8×10^6	5.7×10^8
SKA Phase 2 (Low)($\alpha = -2$)	2.4×10^6	1.2×10^8	2.5×10^{10}

The shallow continuum survey represents (near) all sky northern hemisphere coverage to a sensitivity of $\sim 10\mu Jy$. This survey will provide one of deepest radio catalogues of the northern sky at 1.4 GHz and can be compared with existing radio catalogues to identify transient radio sources. Note, a number of other projects are proposing all sky surveys, such as pulsars and Hı, however these will be conducted commensally (i.e. pulsar and Hı data can be obtained simultaneously with continuum data). The deep surveys offer the largest number of repeat observations of the same field, potentially 500 revisits. In Fig. 5, we include the limit on the snapshot rate that would be found from 500 repeat visits to the same field (labelled 'WSRT + APERTIF (500 Epochs)'). This offers approximately an order of magnitude improvement on the snapshot rate, assuming no transient are detected. Different images could also be averaged together from the deep and medium surveys to improve the sensitivity.

More work is needed to fully characterise the $\log N - \log S$. A top priority should be cadence, the $\log N - \log S$ should evolve to incorporate the characteristic timescale of transient behaviour i.e. $\log N - \log S - \log t$ (see sketch in Fig. 6). Furthermore, this parameter space (including cadence) should be characterised at a number of different radio frequencies (as noted above, the
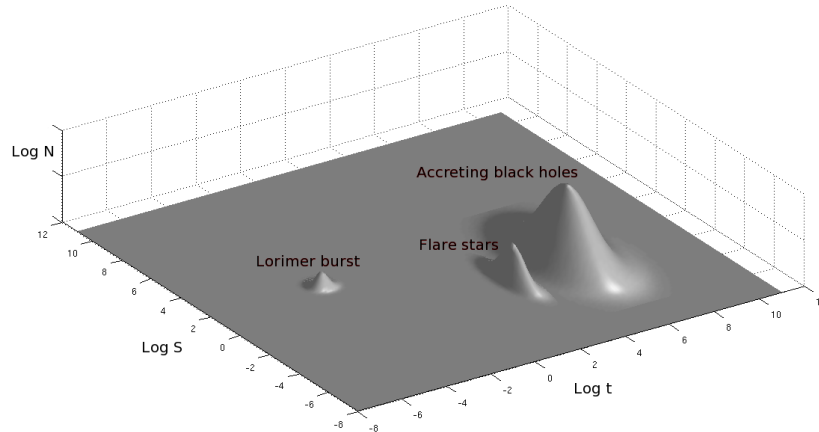
Figure 6. A sketch of possible $\log N - \log S - \log t$ space, illustrating the multi-dimensional nature of the problem, and how current approaches tend to collapse together astrophysically diverse populations.

MHz and GHz transient populations could be significantly different), and also in different directions. For example, in the direction of the Galactic plane, variable radio sources may be more abundant. In a given extragalactic direction, interstellar scintillation may be more prominent (due to increased electron content), and will also potentially increase short timescale variability at low frequencies (e.g. see Hunstead 1972). It may also be interesting to compare (or even normalise) the transient source $\log N$–$\log S$, with the known radio source $\log N - \log S$. For example, Windhorst et al. (1985) have shown that above ~ 1 mJy source populations are dominated by active galactic nuclei, below this star-forming galaxies are thought to dominate (also see Georgakakis et al. 1999 and Carilli et al. 2003).

What shall we do with these huge numbers of radio transients when we find them ? At the time of writing the current goal is to achieve rapid follow-up at optical wavelengths, since this remains the best single tool to characterise the nature of such events. However, this strategy may need to be revised if we find that the population is dominated by sources with no optical counterparts (see e.g. discussion in Bower et al. 2007; Ofek et al. 2010).

5. Conclusion: route inondable

The benchmark study of Bower et al. (2007) is five years old and remains the standard for our understanding of the transient sky at GHz facilities. Several subsequent radio transient searches have delivered upper limits or detections which are consistent with this, but neither significantly refine the statistics nor detect sources in anything close to real time, crucial for multiwavelength follow up and our understanding of the astrophysics of these sources. The new generation of

radio facilities and approved key science projects should change all of this, with near real time reporting of thousands of transient events per year. This in turn will provide an extremely rich resource for multiwavelength follow up, and the possible opening of a new window on the high-energy Universe. Prepare for the flood.

Acknowledgements

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