The Dynamic Radio Sky

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Transient radio sources are necessarily compact and usually are the locations of explosive or dynamic events, therefore offering unique opportunities for probing fundamental physics and astrophysics. In addition, short-duration transients are powerful probes of intervening media owing to dispersion, scattering and Faraday rotation that modify the signals. While radio astronomy has an impressive record obtaining high time resolution, usually it is achieved in quite narrow fields of view. Consequently, the dynamic radio sky is poorly sampled, in contrast to the situation in the X-ray and γ-ray bands. The SKA has the potential to change this situation, opening up new parameter space in the search for radio transients. We summarize the wide variety of known and hypothesized radio transients and demonstrate that the SKA offers considerable power in exploring this parameter space. Requirements on the SKA to search the parameter space include the abilities to (1) Make targeted searches using beamforming capability; (2) Conduct blind, all-sky surveys with dense sampling of the frequency-time plane in wide fields; (3) Sample the sky with multiple fields of view from spatially well-separated sites in order to discriminate celestial and terrestrial signals; (4) Utilize as much of the SKA's aggregate collecting area as possible in blind surveys, thus requiring a centrally condensed configuration; and (5) Localize repeating transient sources to high angular precision, requiring a configuration with long baselines, thus requiring collecting area in both a centrally condensed "core" array and sufficient area on long baselines.

1. Introduction

Transient emission—bursts, flares, and pulses on time scales of order 1 month—marks compact sources or the locations of explosive or dynamic events. As such, radio transient sources offer insight into a variety of fundamental physical and astrophysical questions including

- The mechanisms of efficient particle acceleration;
- Possible physics beyond the Standard Model;
- The nature of strong field gravity;
- The nuclear equation of state;
- The cosmological star formation history;
- Detecting and probing the intervening medium(a); and
- The possibility of extraterrestrial civilizations.

A figure of merit for transient detection is $A\Omega(T/\Delta t)$, where A is the collecting area of the telescope, Ω is the solid angle coverage in the search for transients, T is the total duration of observation, and Δt is the time resolution. Effective detection of transients requires

$$A\Omega\left(\frac{T}{\Delta t}\right) \rightarrow \text{“large”} \quad (1)$$

At high energies (X- and γ-rays), detectors with large solid angle coverage and high time resolution have had great success in finding classes of transient objects. At optical wavelengths there

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has been recent progress in constructing wide-field detectors with high time resolution. Historically, radio telescopes have been able to obtain high time resolution (with some modern telescopes achieving nanosecond time resolution) or large fields of view, but rarely have both high time resolution and large field of view been obtained simultaneously.

Nonetheless, there are a number of indications that the radio sky may be quite dynamic. Radio observations of sources triggered by high-energy observations (e.g., radio observations of gamma-ray burst afterglows), monitoring programs of known high-energy transients (e.g., radio monitoring of X-ray binaries), giant pulses from the Crab pulsar, a small number of dedicated radio transient surveys, and the serendipitous discovery of transient radio sources (e.g., near the Galactic center) suggest that the radio sky is likely to be quite active on short time scales. There also may be unknown classes of sources.

In this chapter, we discuss radio transients from the standpoint of the available phase space that the SKA can probe and how the design of the SKA can be optimized to improve its study of both known and suspected classes of transient radio sources. Several specific classes of radio transients—including pulsars, supernovae and gamma-ray bursts, ultra-high energy cosmic rays, and scintillation-induced variability—are discussed in more depth in additional chapters. We summarize the wide variety of both known and hypothesized radio transients in §2, the available phase space that the SKA can probe in §3, and the operational modes and aspects of transient detection for the SKA in §4.

2. Known and Potential Classes of Transient Radio Sources

Searches for radio transients have a long history, and a wide variety of radio transients are known, ranging from extremely nearby (ultra-high energy cosmic rays impacting the Earth's atmosphere) to cosmological distances (γ-ray bursts). There are also a number of classes of hypothesized classes of transients. In this section we provide an overview of the wide variety of radio transients that the SKA could detect and study.

Ultra-high energy particles: Intense, short-duration pulses ($\sim$ 1 MJy in $\sim$ 1 ns) at frequencies of a few to a few hundred MHz have been observed from the impact of ultra-high energy particles on the Earth's atmosphere [89,25,41]. High-energy neutrinos impacting the lunar regolith should also produce radio pulses near 1 GHz, though searches to date have been unsuccessful in detecting any such pulses [34]. Detection of such particles can place significant constraints on the efficiency of cosmic accelerators, and potentially on the existence of physics beyond the Standard Model of particle physics, if particles with energies beyond the Greisen-Zatsepin-Kuzmin limit ($10^{19.7}$ eV) are detected.

The Sun: Type II and III solar bursts are detected regularly at radio frequencies of tens of MHz [62,73] while solar flares can be detected at tens of GHz [90]. It is not yet clear that the SKA capabilities will extend to frequencies that will optimize studies of the Sun, but, if so, the Sun offers a nearby site to study particle acceleration in detail, particularly when observations are combined with optical, ultraviolet, and X-ray observations.

Planets: Jupiter has long been known to emit radio flares at decameter wavelengths [3,58], and all of the planets with strong magnetic fields (Earth, Jupiter, Saturn, Uranus, and Neptune) produce radio radiation, though not always above the Earth's ionospheric cutoff. At least one of the known extrasolar planets[3] also appears to have a strong magnetic field [79]. By analogy to the solar system planets, Farrell et al. [26], Zarka et al. [93], and Lazio et al. [56] suggest that extrasolar planets would produce bursty emis-

[3] It is worth noting that the first extrasolar planets were discovered using radio observations of the pulsar PSR B1257+12, though any radio emission from these planets is not likely to be detectable.

sion as well. Characteristic frequencies, based on scaling laws from the solar system, suggest that the known extrasolar planets would radiate primarily in the range 10–1000 MHz with flux densities of 10–100 μJy. Detection of radio emission from extrasolar planets would constitute *direct* detection, in contrast to the largely indirect detections of the known extrasolar planets achieved to date from the reflex motions of their hosts stars.

Brown dwarfs: Radio flares have been detected from BD LP944−20 [7], and a survey of late-type stars and brown dwarfs found a number of other objects also exhibiting flares [6]. Typical flare strengths are of order 100 μJy at frequencies between 5 and 8 GHz. The flares are thought to originate in magnetic activity on the surfaces of the brown dwarfs, though some objects have radio emission that deviates from the expected radio–X-ray correlation observed for stars.

Flare stars: Radio flares from various active stars and star systems are observed at frequencies of order 1 GHz with flux density levels that can reach of order 1 Jy [45,75,29] These systems can show strong polarization, including strong circular polarization. These flares are attributed to particle acceleration from magnetic field activity.

Pulsar giant pulses: While all pulsars show pulse-to-pulse intensity variations [39], some pulsars have been found to emit so-called "giant" pulses, pulses with strengths 100 or even 1000 times the mean pulse intensity. The Crab (PSR B0531+21) was the first pulsar found to exhibit this phenomenon. In one hour of observation, the largest measured peak pulse flux of the Crab is roughly $\sim 10^5$ Jy at 430 MHz for a duration of roughly 100 μs [36], corresponding to an implied brightness temperature of 10^{31} K. Recently, pulses with flux $\sim 10^3$ Jy at 5 GHz for a duration of only 2 ns have been detected from the Crab [33]. These "nano-giant" pulses imply brightness temperatures of 10^{38} K, by far the most luminous emission from any astronomical object. For many years, this phenomenon was thought to be uniquely characteristic of the Crab. However, giant pulses have since been detected from the millisecond pulsars PSR B1821−24 [76] and PSR B1937+21 [10] and PSR B0540−69, the Crab-like pulsar in the Large Magellanic Cloud [46].

Transient pulsars: Nice [70] searched for radio pulses along 68 deg^2 of the Galactic plane at 430 MHz. This search resulted in the detection of individual pulses from 5 known pulsars and the discovery of one new pulsar which was previously missed in a standard periodicity search [69]. This pulsar (J1918+08) does not emit giant pulses[4] but is a normal, slow pulsar which fortuitously emitted one strong pulse during the search observations. More recently, Kramer et al. [53] have recognized a class of pulsars that produce pulses only a small fraction of the time. When "on," they appear indistinguishable from normal pulsars. For instance, the 813-ms pulsar PSR B1931+24 is not detectable more than 90% of the time [53], and the 1.8-s pulsar PSR B0826−34 is in a "weak" mode, thought for many years to be a complete null, roughly 70% of the time [24]. Single-pulse searches of the Parkes Multibeam Pulsar Survey data also have resulted in the discovery of several pulsars whose emission is so sporadic that they are not detectable in standard Fourier domain searches [64].

X-ray binaries: Large radio flares, with peak flux densities during an outbursts being factors of 10–100 larger than quiescence, have long been known from X-binaries such as Cygnus X-3 [87,27]. Search for short-duration, single pulses from the X-ray bi-

[4] We define giant pulses as those comprising a long tail on the overall pulse amplitude distribution; for the Crab pulsar and the millisecond pulsars B1937+21 and B1821−24, these tails are power-law in form.

naries Scorpius X-1 and Cygnus X-1 have been unsuccessful, though [82].

Soft γ-ray repeaters: Vaughan & Large [86] conducted an unsuccessful search for radio pulses from the soft γ-ray repeater SGR 0526−66.

Maser flares: The emission from OH masers can vary on timescales of hundreds of seconds and be detected as long-duration radio bursts [11,92].

Active galactic nuclei: Active galactic nuclei (AGN) outbursts, likely due to propagation of shocks in relativistic jets, are observed at millimeter and centimeter wavelengths [1,54].

Intraday variability: Intraday variability (IDV), resulting from interstellar scintillation of extremely compact components ($\sim 10\ \mu$as) in extragalactic sources, occurs at frequencies near 5 GHz. The typical modulation amplitude is a few percent and is both frequency and direction dependent, but occasional rare sources are seen to display much larger amplitude modulations with timescales of hours to days [50,60]. Intraday variability could be an important issue for calibration and imaging of the SKA as existing surveys suggest that it becomes more prevalent at lower flux densities (< 100 mJy).

Radio supernovae: With the goal of detecting the single, large, broadband radio pulse (< 1 s) expected to be emitted at the time of a supernova explosion [12], Huguenin & Moore [43] and Kardashev et al. [48] performed radio searches for single pulses, but found no convincing signals of extraterrestrial origin aside from solar flares.

γ-ray bursts: In searches for radio pulses associated with γ-ray bursts, Cortiglioni et al. [18], Inzani et al. [44], and Amy et al. [2] detected some dispersed radio pulses, but found no convincing associations with gamma-ray burst sources. Balsano [5] found a dispersed radio pulse apparently coincident with GRB980329; however, it was narrowband, which has led to it being interpreted as due to terrestrial interference. Various searches for radio pulses associated with gamma-ray bursts (including precursor pulses) have been conducted at 151 MHz [51,52]. Typical upper limits have been approximately 100 Jy. Theoretically, Usov & Katz [85] and Sagiv & Waxman [77] have predicted that gamma-ray bursts should have associated prompt emission, most likely below 100 MHz.

Gravitational wave sources: In a search for radio counterparts to the gravitational pulses reported by Weber [88], both Hughes & Retallack [42] and Edwards et al. [23] detected excesses of radio pulses from the direction of the Galactic center, but did not believe them to be correlated with the gravitational pulses. More recently Hansen & Lyutikov [38] have predicted that inspiraling neutron star-neutron star binaries could produce radio precursors to the expected gravitational wave signature.

Annihilating black holes: O'Sullivan et al. [71] and Phinney & Taylor [72] conducted searches for radio bursts at frequencies near 1 GHz possibly associated with annihilating black holes, as suggested by Rees [74], but likewise found no convincing signals.

Extraterrestrial transmitters: While no such examples are known of this class, many searches for extraterrestrial intelligence (SETI) find non-repeating signals that are otherwise consistent with the expected signal from an extraterrestrial transmitter. Cordes et al. [16] discuss how extraterrestrial transmitters could appear to be transient, even if intrinsically steady.

3. Exploring Phase Space

For definiteness, we consider transients as those objects or emission phenomena that show substantial flux density changes on time scales of one month or less. Although our upper limit on relevant time scales is arbitary, the lower limit is set by the physics in the source. For instance, the pulsar with the shortest known pulse period is PSR B1937+21 for which $P = 1.56$ ms, while some giant pulses from the Crab pulsar have substructure at 5 GHz as short as approximately 2 ns [33]. Extensive air showers have been hypothesized to have time scales as short as 1 ns.

In the Rayleigh-Jeans approximation, a source with brightness temperature T varies (intrinsically) on a time scale or pulse width W given by

$$W^2 = \frac{1}{2\pi k}\frac{SD^2}{T}\frac{1}{\nu^2}, \qquad (2)$$

where the observed flux density is S, the source's distance is D, the emission frequency is ν, and k is Boltzmann's constant. Figure 1 shows the phase space of the pseudo-luminosity SD^2 vs. νW. There are two notable aspects of this figure. First, the transient radio sources observed span a large range in this phase space. The range of νW covers at least 13 orders of magnitude while the range of SD^2 covers at least 20 orders of magnitude. Second, large portions of this phase space are empty.

One of two conclusions can be drawn from Figure 1. One could conclude no physical mechanisms or sources exist that would populate the empty regions in the phase space of Figure 1. Alternately, we regard Figure 1 as an illustration of the incompleteness of our knowledge of the transient radio sky and of the potential for the SKA.

In order for the SKA to explore the dynamic radio sky, "equation (1)" must be satisfied; it must obtain large solid angle coverage, high time resolution, and high sensitivity simultaneously. We discuss the time resolution requirements in more detail below. Figure 2 illustrates that, historically, radio telescopes have been capable of obtaining either large solid angle coverage (e.g., the STARE survey at 610 MHz by Katz et al. [49] with a FWHM beam of 4000′) or high sensitivity (e.g., the Arecibo telescope with a gain of 11 K Jy^{-1} at 430 MHz) but not the two simultaneously. If the SKA satisfies its design re-

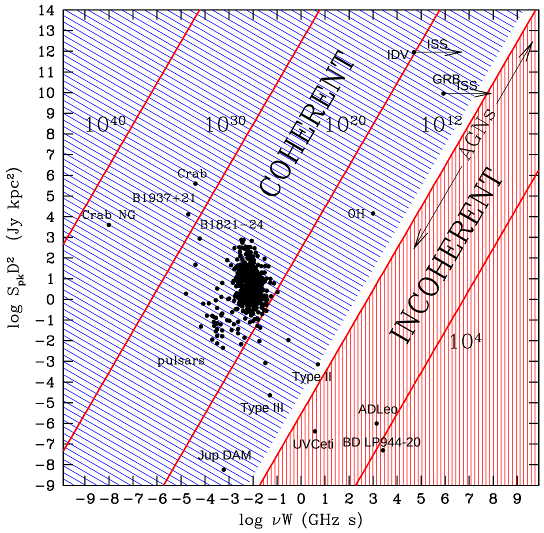

Figure 1. The phase space for radio transients. The abscissa is the product of the emission frequency ν and transient duration or pulse width W. The ordinate is the product of the observed flux density S and square of the distance D^2. In the Rayleigh-Jeans approximation, these quantities are directly proportional and related to the brightness temperature T (eqn. 2). The sloping lines are labelled by constant brightness temperature. A brightness temperature of 10^{12} K is taken to divide coherent from incoherent sources. Examples of transient emission from various classes of sources are indicated. In the case of gamma-ray burst afterglows (GRB) and intraday variability (IDV) of active galactic nuclei (AGN), the apparently high brightness temperatures are not thought to be intrinsic but related to interstellar scintillation (ISS). For these two classes of sources we show how the absence of ISS would affect their locations in this phase space.

quirements, it will produce at least an order of magntiude sensitivity improvement, over a large frequency range, with a solid angle coverage that is comparable to or exceeds that of all but a small number of low-sensitivity telescopes.

4. SKA Operational Modes and Experiments

The SKA is most likely to open up new areas of parameter space or discover new classes of sources by conducting dedicated transient searches. For a fixed collecting area A and fixed total telescope time, the transient figure of merit (equation 1) can be optimized either by covering as much solid angle as possible ("tiling") or by observing as deeply as possible ("staring"). Various optimizations are possible, depending upon the class of transient being sought, what is known about the typical duration and sky distribution of the class, and the importance of interstellar scintillations [17,68,14]. We consider a spectrum of possible transient searches, ranging from a "pure" staring search (extrasolar planets) to a "pure" tiling search (an all-sky survey). Our examples are by no means the only classes of potential transients that are amenable to these methods of searching, but they represent classes for which the sensitivity of the SKA is either essential or produces qualitatively larger numbers of such transients to be detected.

In addition, we envision that a host of traditional radio transient studies will be possible with the SKA. Much like current interferometers, the SKA will be able to respond to triggers from other wavelengths. Current examples of this capability include responding to γ-ray bursts, supernovae, and X-ray transients. With its high sensitivity and high angular resolution, the SKA will both continue and improve on existing studies.

The SKA should also be capable of conducting monitoring experiments, possibly used to trigger observations at other wavelengths. In many current concepts, the SKA is envisioned as having a "core" and "outlying stations." (Indeed, below we discuss why such a configuration is necessary for the SKA for transient searching.) Not all observations will be able to make use of the

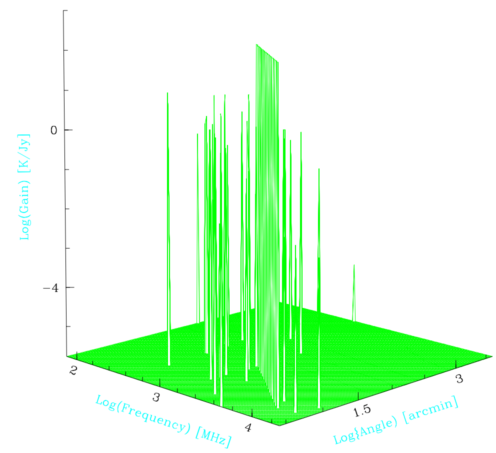

Figure 2. A representation of the combined frequency coverage, solid angle coverage, and sensitivity of a variety of historical and existing radio telescopes. The solid angle coverage is shown as the FWHM dimension of the beam (or equivalent) in arcminutes. The sensitivity is shown as the gain in units of K Jy^{-1}. All scales are *logarithmic*. For reference, the largest angle coverage is provided by the 610 MHz STARE survey with a FWHM beam equivalent of $4100'$ while the most sensitive telescope other than the SKA is the Arecibo telescope with a 430 MHz gain of 11 K Jy^{-1}. The SKA is shown assuming that it has a $60'$ field of view at 1 GHz, which scales as ν^{-1}, and that it has an effective collecting area in the "core" of $500\,000\ \mathrm{m}^2$, which is constant between 1 and 10 GHz. Not shown is the EVLA which will have a similar frequency coverage but an angle coverage of 4 times smaller and a sensitivity of 75 times less.

entire SKA, e.g., use of the outlying stations produces too low of a surface brightness sensitivity for some kinds of H I observations. Thus, a small number of outlying stations could be used to form a subarray and tasked to measure the flux density of a variety of objects, such as to search for changes resulting from flares from X-ray binaries or extreme scattering events (ESEs) toward active galactic nuclei.

4.1. Staring at Extrasolar Planets

The past few years have been an exciting time as extrasolar planets have been demonstrated to be widespread and multiple planetary systems have been found. The current census now numbers more than 100 extrasolar planets, in over 90 planetary systems [78,63].

The vast majority of these extrasolar planets have been detected via the reflex motion of the host star. As the existing census shows, this method has proven to be wildly successful. Nonetheless, the reflex motion of the star is a measure of the planet's gravitational influence and is necessarily an *indirect* detection of the planet. As a consequence, the only property of the planet that one can infer is its mass, and because of the mass function's dependence on the inclination angle ($\sin i$), one can infer only a minimum mass.

Direct detection of reflected, absorbed, or emitted radiation from a planet allows for the possibility of complementary information, and likely a more complete characterization of the planet. The prototype of such a direct detection is the detection of sodium absorption lines in the atmosphere of the planet orbiting HD 209458 [9]. Unfortunately, the incidence of transiting planets will always remain low relative to the total number of planets known.

The Earth and gas giants of our solar system are "magnetic planets" in which internal dynamo currents generate a planetary-scale magnetic field. The radio emission from these planets arises from coherent cyclotron emission due to energetic (keV) electrons propagating along magnetic field lines into active auroral regions [32,91]. The source of the electron acceleration to high energies is ultimately a coupling between the incident solar wind and the planet's magnetic field, presumably due to magnetic field reconnection in which the magnetic field embedded in the solar wind and the planetary magnetic field cancel at their interface, thereby energizing the plasma. Energetic electrons in the energized plasma form a current flow planet-ward along the planet's magnetic field lines, with the lines acting effectively like low resistance wires. The energy in these magnetic field-aligned electric currents is deposited in the upper polar atmosphere and is responsible for the visible aurora. Besides auroral emissions at visible wavelengths (e.g., northern lights), about 10^{-5}–10^{-6} of the solar wind input power is converted to escaping cyclotron radio emission [32]. The auroral radio power from Jupiter is of order $10^{10.5}$ W.

At least one of the known extrasolar planets is also a magnetic planet. Shkolnik, Walker, & Bohlender [79] have detected a modulation in the Ca II H and K lines of HD 179949 with a periodicity which is that of the planetary orbit. They interpret this as a magnetic interaction between the star and planet, though there is no constraint as yet on the magnetic field strength of the planet.

The SKA offers the possibility of detecting radio emission from extrasolar planets. Detection of radio emission from an extrasolar planet would constitute a *direct* detection and can yield fundamental information about the planet. First, a measurement of the radio emission is directly indicative of the polar magnetic field strength at the planet. For example, the high-frequency cutoff of Jovian decametric bursts ($\simeq$ 40 MHz) is interpreted as being due to the Jovian polar magnetic field strength, which allowed an estimate for the strength of the Jovian magnetic field nearly 20 yr prior to the first *in situ* magnetic field observations. In turn, the presence of a magnetic field provides a rough measure of the composition of the planet, insofar as it requires the planet's interior to have a conducting fluid. Combined with an estimate of the planet's mass, one could deduce the composition of the fluid by analogy to the solar system planets (liquid iron vs. metallic hydrogen vs. salty ocean).

Second, the periodic nature of the radio emission has been used to define precisely the planetary rotation periods of all of the gas giant planets in the solar system, because the magnetic field is presumed to be tied to the interior of the planet.

Finally, testing the extent to which solar-system models of magnetic fields can be applied to extrasolar planets may have important implications for assessing the long-term "habitability" of terrestrial planets found in the future. The importance of a magnetic field is that it deflects incident cosmic rays. If these particles reach the surface of an otherwise habitable planet, they may cause severe cellular damage and disruption of genetic material to any life on its surface or may prevent life from arising at all. A secondary importance of a magnetic field is that it can prevent the planet's atmosphere from being eroded by the stellar wind [67]; this process is thought to be a contributing factor to the relative thinness of the Martian atmosphere. (This is of course unlikely to be an issue for extrasolar giant planets.)

Farrell et al. [26], Zarka et al. [93], and Lazio et al. [56], building on empirical relations derived for solar system planets and calibrated by spacecraft fly-bys, have made specific predictions for the radio emission from the known extrasolar planets. Their predictions have made use of two empirical relations, *Blackett's Law* and the *Radiometric Bode's Law*.

Blackett's law relates a planet's magnetic moment (its surface field times its radius cubed, BR^3) to its rotation rate and mass. The Radiometric Bode's law relates the incident stellar wind power and the planet's magnetic field strength to its median emitted radio power.

The predicted radio power for a magnetic planet immersed in its host's star stellar wind is

$$P_{\mathrm{rad}} \sim 4\times 10^{11}\,\mathrm{W} \left(\frac{\omega}{10\,\mathrm{hr}}\right)^{0.79} \left(\frac{M}{M_J}\right)^{1.33} \left(\frac{d}{5\,\mathrm{AU}}\right)^{-1.6}, \quad (3)$$

where ω is the planet's rotation rate, M is its mass, and d is the distance between the planet and host star. All quantities have been normalized to those of Jupiter. Farrell et al. [26] discussed slight differences to this radiometric Bode's law derived by various authors; the differences result from the statistical spread in the various (solar system) planets' magnetic moments and amount to slightly different exponents and/or a different coefficient.

We stress various aspects of this radiometric Bode's law. First, it is grounded in *in situ* measurements from spacecraft fly-bys of the gas giants as well as measurements of the Earth's radio emission.

Second is the importance of the planet-star distance. As Zarka et al. [93] show, the radio power from Earth is larger than that from Uranus or Neptune even though both of those planets have magnetic moments approximately 50 times larger than that of the Earth.

Third, the radiometric Bode's Law of equation (3) describes the *median* emitted power from the magnetospheres of the Earth and all of the solar gas giants, including the *non-Io driven* Jovian decametric radio emission [93]. Planetary magnetospheres tend to act as "amplifiers" of the incident solar wind, so that an increase in the solar wind velocity (and therefore incident pressure) leads to geometrically higher emission levels. This effect is observed at all of the magnetized planets. Based on the range of solar wind velocities and emitted radio powers observed at the Earth [**?**, Figure 5]e.g.,]gd81, the radio power levels from a planet can exceed that predicted by equation (3) by factors of 100 and possibly more.

The required quantities for applying equation (3) are the planet's mass, distance from its primary, and rotation rate. The radial velocity method determines a lower limit to the planet's mass (i.e., $M \sin i$) and the semi-major axis of its orbit. We have no information on the rotation rates of these planets. We have therefore assumed that those planets with semi-major axes larger than 0.1 AU have rotation rates equal to that of Jupiter (10 hr), while those with semi-major axes less than 0.1 AU are tidally-locked with rotation rates equal to their orbital periods [30,83]. Figure 3 presents the expected *median* flux densities vs. the emission frequency in a graphical form.

The trend in Figure 3 of increasing emission frequency and decreasing flux density is real and reflects two effects. First, the lower envelope reflects a selection effect. A low flux density and

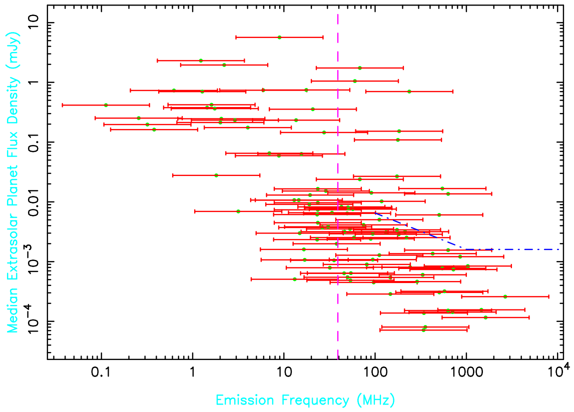

Figure 3. The *median* predicted flux densities for 106 known extrasolar planets vs. the characteristic emission frequency based on the radiometric Bode's Law and Blackett's Law. The horizontal bars indicate the assumed ranges for the emission frequencies, allowing the statistical variations from Blackett's Law in the estimated planetary magnetic moments. The vertical dashed line indicates the cutoff frequency for Jupiter's radio emission. The dot-dashed line shows the sensitivity of the SKA, assuming an integration time of 15 min. and a bandwidth of 4 MHz. For the SKA, a nominal sensitivity of $A_{\rm eff}/T_{\rm sys}$ = $5000\,{\rm m}^2\,{\rm K}^{-1}$ has been assumed at 100 MHz, improving to $20\,000\,{\rm m}^2\,{\rm K}^{-1}$ at 1000 MHz.

small emission frequency results from a low-mass planet in a large orbit. These planets cannot be detected with the current detection methodology. Second, the upper envelope reflects the well-known deficit of planets with both large masses and small semi-major axes. Even if high-mass planets with close orbits did exist, however, they probably would be tidally locked (as we have assumed here). The rotation rate also determines the strength of the magnetic field, so tidally-locked planets probably do not radiate at high emission frequencies. However, [94] have suggested that such "hot Jupiters" may radiate by the conversion of stellar magnetic pressure (which is large in close to the star) into electromotive forces, currents, and radio emission.

In designing an experiment to detect extrasolar planets, staring is clearly the preferred method as the locations of the planets are known and covering large solid angles would not increase the odds of detection. However, the potential for bursts must be taken into account. The sensitivity of a radio telescope improves with increasing integration time as $t^{-1/2}$. Longer integration times improve the sensitivity but at the cost of "diluting" any bursts. For a burst of flux density S_b and duration Δt_b, its average flux density in an integration time t is $S_b(\Delta t_b/t)$, i.e., the burst is diluted with time as t^{-1}. To the extent that extrasolar planet radio emission is "bursty" (as is observed for the solar system planets), multiple short observations are a better strategy than a single long integration.

Current design goals for the SKA specify its sensitivity to be $A_{\rm eff}/T_{\rm sys}$ = $5000\,{\rm m}^2\,{\rm K}^{-1}$ at 100 MHz, improving to $20\,000\,{\rm m}^2\,{\rm K}^{-1}$ at 1000 MHz. In a 15 min. integration, its flux density sensitivity would be in the range 1–10 μJy, more than sufficient to detect the radio emissions from the most massive extrasolar planets, without relying upon bursts to enhance the emission levels. If bursts are considered, the SKA should detect a substantial fraction of the current census, if the bursts are comparable in magnitude to what is seen in the solar system (factors of 10–100).

4.2. Giant Pulses from Extragalactic Pulsars

As discussed above, the Crab pulsar and a small number of other pulsars are known to emit giant pulses, pulses that comprise a long tail on the overall pulse amplitude distribution. These probably arise from coherent emission within the turbulent plasma in the pulsar magnetosphere [33]. Some of these pulses are so strong that, were the Crab pulsar located in a nearby external galaxy, it could be detected with existing telescopes. Exploiting both the SKA's sheer sensitivity and flexibility, giant pulses from pulsars in external galaxies should be detectable well beyond the Local Group and potentially to the distance of the Virgo Cluster.

The fraction of its lifetime over which a pulsar might exhibit the giant pulse phenomenon is not known. If we take the Crab as an exemplar of young, giant-pulse emitting pulsars, we might expect a birth rate of order 1 pulsar per 100 yr and that the giant pulse phenomenon lasts for of order 1000 yr. With careful accounting for selection effects (e.g., pulsar beaming fraction), giant-pulse emitting pulsars in external galaxies can probe the recent massive star formation in those galaxies.

Moreover, by their dispersion measures (DM) and rotation measures (RM), extragalactic pulsars have the potential to probe the baryon density and magnetic field in the Local Group and potentially beyond. Current models for large-scale structure formation predict that matter in the current epoch forms a "cosmic web" [8,19,20]. Most of the baryons in the Universe reside in large-scale filaments that form the "strands" of the web, with groups and clusters of galaxies located at the intersections of filaments. At the current epoch, hydrogen gas continues to accrete onto and stream along these filaments, undergoing multiple shocks as it falls into the gravitational potential wells located at the intersections of the filaments. In this model, the filaments of hydrogen form a warm-hot ionized medium (WHIM), with a temperature of 10^5–10^7 K.

Recent observations of highly ionized species of oxygen and neon by both the *FUSE* and *Chandra* observatories are considered to be validations of these predictions. Absorption observations along various lines of sight suggest a diffuse medium with a temperature of order 10^6 K with a density of order 5×10^{-5} cm^{-3}. While striking, these observations still suffer from the difficulty of probing only trace elements. The ionized hydrogen in the WHIM has not been detected directly, but, over megaparsec path lengths, the implied DMs are of order 50 pc cm^{-3}, comparable to or larger than that for nearby pulsars.

For the Crab pulsar, the most well-studied giant-pulse emitting pulsar, the giant pulse amplitude distribution is power-law in form at high amplitudes [61,13]. On average, the strongest pulse observed from the Crab pulsar at 0.43 GHz in one hour has a signal-to-noise ratio of $S/N_{\rm max} \approx 10^4$, even with the system noise dominated by the Crab Nebula. For objects in other galaxies, the system noise is essentially unaffected by any potential nebular contribution. If the Crab pulsar were not embedded in its nebula, the S/N of such a pulse would be larger by the ratio of the system noise equivalent flux density when observing the Crab Nebula to the nominal system noise equivalent flux density or $S_{\rm CN}/S_{\rm sys_0} \approx 300$ times larger, or 3.3×10^6. Thus, on average, in an hour's observation, one should be able to detect a Crab-like pulsar to a maximum distance at a specified signal-to-noise ratio, $(S/N)_{\rm det}$,

$$\begin{aligned} D_{\rm max} & \\ = \quad & D_{\rm CN}\left[\frac{(S/N)_{\rm max}}{(S/N)_{\rm det}}\left(1+\frac{S_{\rm CN}}{S_{\rm sys_0}}\right)-\frac{S_{\rm CN}}{S_{\rm sys_0}}\right]^{1/2} \\ \approx \quad & 1.6\,{\rm Mpc}\left[\frac{(S/N)_{\rm det}}{5}\right]^{-1/2}\left(\frac{f_c A_{\rm SKA}}{A_{\rm AO}}\right)^{1/2}, \end{aligned} \tag{4}$$

where $f_c A_{\rm SKA}$ is the SKA's collecting area that can be used for a giant pulse survey and $A_{\rm AO}$ is Arecibo's effective area at 0.43 GHz. The usable area for the SKA in a blind survey will be limited by what fraction f_c of the antennas are directly connected to a central correlator/beamformer. For $f_c = 1$, $A_{\rm SKA}/A_{\rm AO} \approx 20$ so the standard one-hour pulse seen at Arecibo could be detected to 7.3 Mpc. Figure 4 shows that even for more modest values of f_c, e.g., $f_c \approx 0.3$, the SKA could detect giant-pulse emitting pulsars well beyond

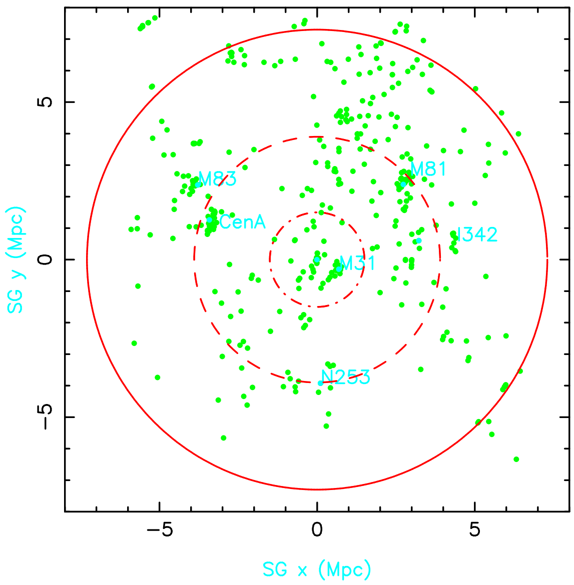

Figure 4. The distance to which a Crab giant pulse can be detected. The three circles show (in order of increasing size) the distance to which the strongest pulse detected in 1 hr using Arecibo (5% of the SKA, assuming that it could see the entire sky), 30% of the SKA, and the full SKA. The distribution of local galaxies is shown in the Supergalactic x and y planes (from [47]), and certain galaxies or groups of galaxies are labelled.

the Local Group.

No upper amplitude cutoff has been observed yet for the Crab pulsar's giant pulse amplitude distribution [61]. Observing for longer than 1 hr results in even stronger pulses being detected. Assuming that the Crab pulsar is not atypical, a modest extrapolation of the giant pulse amplitude distribution implies that the SKA could detect giant-pulse emitting pulsars in the Virgo cluster ($D \approx 20$ Mpc).

An additional efficiency is obtained toward the Virgo cluster as many galaxies will be contained within the SKA's field of view. Although it is not yet clear what frequency would be optimal for a giant-pulse search toward the Virgo cluster, it almost certainly will be not much higher than 1 GHz. Thus, the field of view will be at least 1 deg.^{2} and could be potentially nearly 10 times larger, e.g., for observations at 0.33 GHz.

The baryon density along the line of sight to an extragalactic giant-pulse emitting pulsar can be inferred from the pulsar's DM. The dispersion measure is simply the line-of-sight integral of the electron density, DM $= \int n_e\, dl$. As is the case for more traditional pulsar searches, giant pulse searches require dedispersion, which is accomplished by searching through a number of trial DMs [65]. As a line-of-sight integral, the DM for an extragalactic pulsar contains contributions from the Galaxy, the intergalactic medium, and the host galaxy(ies). The Galactic contribution to the DM can be predicted from models for the Galactic free electron distribution [15], and in the SKA era even more detailed models will be available. However, the contribution from the host galaxy will be able to be estimated only crudely (e.g., from its inclination and assuming a plane-parallel electron density distribution). We anticipate that the uncertainty in separating the host galaxy and intergalactic contributions to the DMs of extragalactic pulsars will scale roughly as $\sqrt{N}$ for N extragalactic pulsars. Thus, it is not sufficient merely to detect one or a few extragalactic pulsars, as might be accomplished with existing telescopes (like the 100-m Efflesberg telescope, the Green Bank Telescope, or Arecibo).

Similar considerations apply to the measurement of the intergalactic magnetic field via the rotation measure, RM $= \int n_e \mathbf{B} \cdot \mathbf{dl}$. Measurement of the RM for extragalactic pulsars would prove a unique probe of the magnetic field in the Local Supercluster, but this requires the detection of many extragalactic pulsars to separate the Galactic, host galaxy, and intergalactic contributions.

Searching for giant pulses from extragalactic pulsars requires time-domain searches, i.e., it is a *non-imaging* application of the SKA. In order to conduct these searches, there are three key requirements for the SKA. The first is that it have the capability to provide, in a routine manner, fast-sampled data. Given that part of the motivation for transient searching is to open up new parameter space, an arbitarily fast sampling may appear necessary. There are, however, certain physically-motivated limits that can be specified. First, in order to accomplish the Key Science Driver of "Strong Field Tests of Gravity Using Pulsars and Black Holes" a minimum time sampling of 10 μs is required in order to conduct pulsar timing observations. Lazio & Cordes [57] summarized various interstellar propagation effects that suggest that a time sampling faster than a few microseconds is not justified, at least for sources at interstellar or intergalactic distances at frequencies near 1 GHz. These effects are strongly frequency dependent, though, so nanosecond time sampling can be tolerated at frequencies above 5 GHz, as evidenced by the Crab pulsar's nano-giant pulses. Finally, the coherent pulses from ultra-high energy cosmic ray impacts on the Earth's atmosphere have time scales of order 1 ns. Thus, a useful target range for the SKA would be sampling times between 1 ns and 10 μs.

The second requirement for the SKA is on its configuration. Backer [4] has shown that the signal-to-noise ratio achieved in a search scales with the array filling factor f as $\sqrt{f}$. Thus, the SKA should have a reasonably compact "core" where the filling factor is not too small. A useful goal might be a core containing a significant fraction of the SKA collecting area ($\sim$ 50%) with a filling factor of a few percent to 10%.

A third requirement is on effective suppression of radio frequency interference (RFI). This requirement is not unique to searches for transients, of course, but it is perhaps more stringent for transient searching than for other operational modes. One wishes to ensure that cosmic transient signals are not confused with terrestrial RFI and thereby eliminated. A variety of techniques may end up being applied with the SKA, but two key techniques for extragalactic giant pulses and other fast transients are utilizing the spatial extent of the SKA and the expected dispersion smearing of the signals. Cordes & McLaughlin [14] illustrate how dispersion smearing can be used advantageously. Briefly, any pulse from a source outside the solar system will suffer dispersion smearing while most terrestrial RFI will not. Similarly, terrestrial RFI should not affect all SKA antennas equally whereas a celestial pulse should, taking into account the time delay between the antennas. The spatial extent of the SKA (or of its core) can be used as an anti-coicidence filter to identify RFI.

Finally, targeted transient searches could be conducted in a "piggyback" synthesis mode. The relatively large field of view of the SKA implies that most continuum synthesis observations will be conducted in a pseudo-continuum mode, so as to be able to image the entire field of view without significant bandwidth smearing. The positions and flux densities of most of the "strong" sources ($>$ 10 mJy) in any given field of view should be known reasonably accurately (from surveys like the NVSS) and could be subtracted from the visibility data. The residual visibility data could then be imaged on different time scales to search for weak point sources that vary. Such a piggyback mode would be particularly effective at finding moderate duration transients in nearby galaxies and clusters of galaxies.

4.3. Tiling the Sky: An All-Sky Survey

An all-sky survey would be designed to search for transients of unknown or poorly known duration and distribution. As a strawman for such a survey, we take the goal of surveying an entire hemisphere within 24 hr. If the SKA meets its current specification of a 1 deg^2 field of view, then each pointing can be 1 s in duration (assuming Nyquist sampling of the sky). Allowing for 50% efficiency, assuming a bandwidth of only 1 MHz, and only half of the collecting area of the SKA (in its core), such a blind, all-sky survey would still obtain a typical noise level of approximately 0.5 mJy. Larger bandwidths or a larger fraction of the SKA collecting area in the core or both would improve upon this noise level, though larger bandwidths could also imply a heavier computational load in order to cope with increased DM searching. Similarly, the sky could be covered more quickly at lower sensitivity by dividing the SKA into sub-arrays, each having the same 1 deg.^{2} field of view but reduced sensitivity.

One manner in which an all-sky search would not be challenging would be the slew rate. The implied slew rate is comparable to what current instruments provide, e.g., for the VLA the slew rate is approximately 0.5 deg. s^{-1}.

A less ambitious "blind" survey would be a survey along the Galactic plane. Existing Galactic plane surveys [55] have provided intriguing hints of transients to be detected. Such a survey might also be possible in the early years of the SKA, before the full computational infrastructure is in place or as an initial effort before searching the entire sky. As a strawman survey we consider a 12-hr survey covering 90° of Galactic longitude and 10° in Galactic latitude ($|b| < 5°$). Covering 900 deg^2, again with a 1 deg^2 field of view at 1 GHz, would allow for approximately 10 s per pointing and produce an rms noise of approximately 0.1 mJy. Alternately, a higher frequency could be used (to reduce the impact of dispersion smearing or any possible pulse broadening) at the cost of less time per pointing, a slightly higher noise level, and a loss of sensitivity to steep spectrum sources. For instance, at 3 GHz, the time per pointing would be 1 s.

A key aspect of transient searches will be sufficient computational power. A full analysis will not be possible until the SKA concept is chosen (as that will affect issues such as the field of view). For a strawman analysis, though, consider an imaging-based search in which a correlator produces an image which is then examined for transients. Preliminary considerations imply that imaging the full FOV is more efficiently done through correlation than through direct beam forming.

At each integration time the number of correlations to be computed is

$$N_{\rm c} = \frac{1}{2} n_{\rm a}(n_{\rm a}-1) N_{\rm pol} N_{\nu}, \tag{5}$$

where $n_{\rm a}$ is the number of antennas, $N_{\rm pol}$ is the number of polarization channels ($N_{\rm pol} = 4$ for full Stokes), and N_{ν} is the number of frequency channels. The number of pixels in the FOV for a maximum baseline, $b_{\rm c}$, in the core array and an aperture diameter D is

$$\begin{aligned} N_{\rm pix} &\approx 0.85 \left(\frac{b_{\rm c}}{D}\right)^2 \\ &\approx 10^4 \,\text{pixels}\, (b_{\rm c,km}/D_{10})^2 . \end{aligned} \tag{6}$$

For fast transients (e.g. durations $\lesssim$1 sec), sufficient channels are needed to allow dedispersion, a requirement that also satisfies the need for the "delay-beam" to be large enough for full FOV mapping. Dedispersion in blind surveys requires summing over frequency with trial values of DM, whose number is approximately the same as the number of channels. Additional processing would include matched filtering to identify individual transients and Fourier analysis to find periodic sources. For SETI and other spectral-domain searches, each pixel would be Fourier analyzed (before detection) to identify candidate spectral lines.

Table 1
SKA Requirements for Transient Surveys

Parameter	Requirement
Field of View (at 1 GHz)	1 deg.^{2}
Time Sampling	$\sim$ 1 ns to 10 μs
Frequency Coverage	$\sim$ 0.1–10 GHz
Configuration	"large" core filling factor long baselines

5. Conclusions

Transient radio sources offer insight into dynamic or explosive events as well as being powerful probes of intervening media. Historically, the radio sky also has been searched only poorly for radio transients, meaning that the SKA has the potential to explore previously-unexplored parameter space at radio wavelengths.

In order to be effective at searching for transient radio sources, the SKA must achive a "large" value for the figure of merit $A\Omega(T/\Delta t)$, equation (1). By its very nature, A is anticipated to be large for the SKA. Table 1 summarizes the other requirements on the SKA. These requirements flow either from the desire to achieve a large figure of merit or are based on experience from known radio transients.

In order to conduct successfully the Key Science Project, "Strong Field Tests of Gravity Using Pulsars and Black Holes," the SKA is required to obtain high time resolution. The challenge for the SKA, and historically the difficulty with radio telescopes, is that they have not provided a large field of view simultaneously with high sensitivity.

A related requirement is on the configuration of the array, as the filling factor of the array affects the signal-to-noise ratio in a search as $\sqrt{f}$. Thus, the SKA requires a core, containing a significant fraction of the collecting area with a reasonablely high filling factor, as well as long baselines, for localizing sources and imaging searches such as for γ-ray bursts and extrasolar planets.

From known classes of sources alone, this search promises to be fruitful—one can explore particle acceleration by observing radio pulses from ultra-high energy particles impacting the Earth's atmosphere as well as from flares from the Sun, brown dwarfs, flare stars and X-ray binaries while using afterglows from γ-ray bursts one can explore the cosmological star formation history. Likely, though not yet detected, classes of sources include giant pulses from extragalactic pulsars, which would allow a direct probe of the local intergalactic medium, and extrasolar planets, which would be a direct detection of these objects.

Most exciting would be the *discovery of new classes of sources.*

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