The Dynamic Radio Sky: An Opportunity for Discovery

J. Lazio[1] (NRL), J. S. Bloom (UC Berkeley), G. C. Bower (UC Berkeley), J. Cordes (Cornell, NAIC), S. Croft (UC Berkeley), S. Hyman (Sweet Briar), C. Law (UC Berkeley), & M. McLaughlin (WVU)

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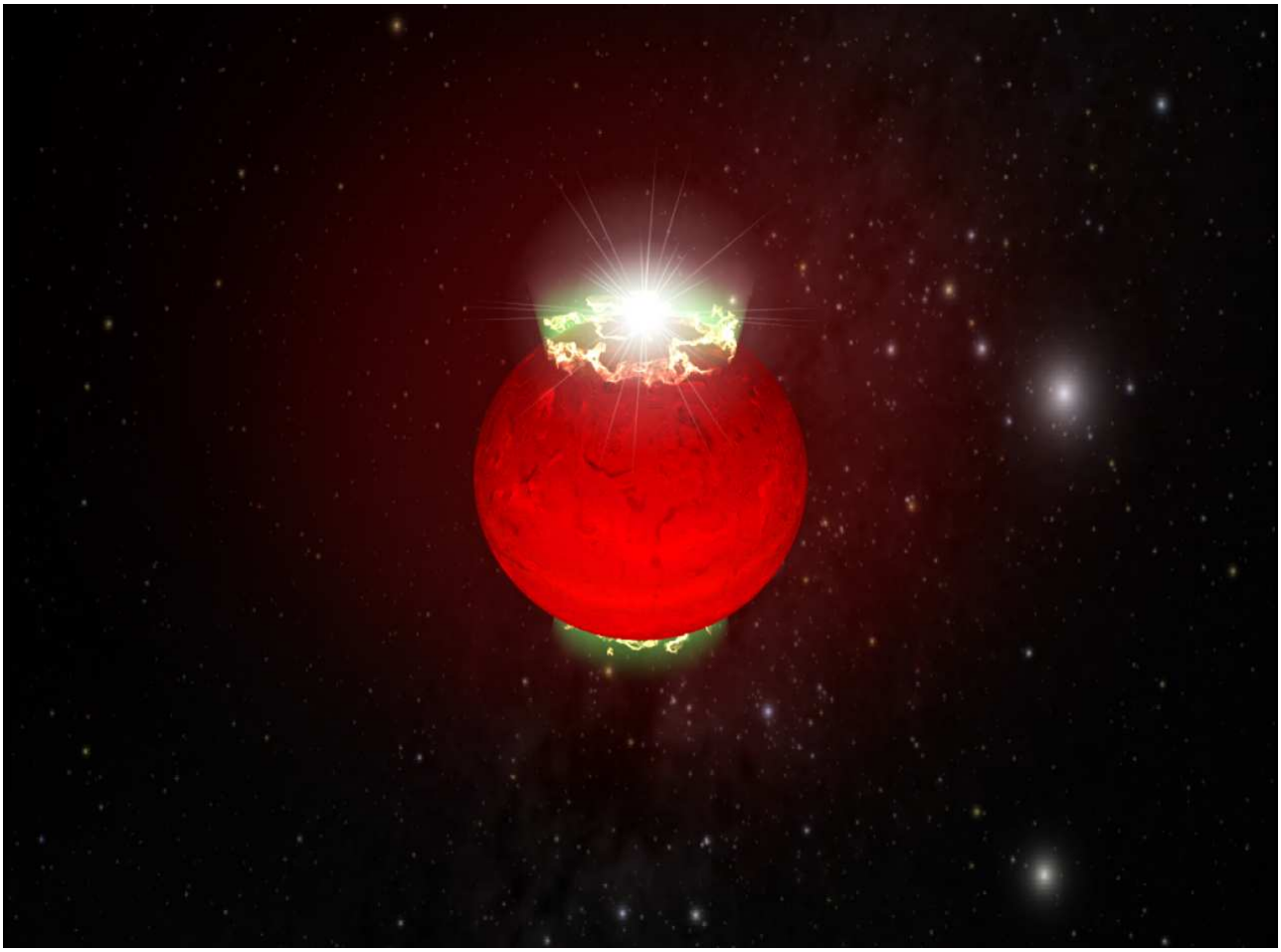

[1] Contact information: 202-404-6329, *Joseph.Lazio@nrl.navy.mil*; Image credit: Hallinan et al., NRAO/AUI/NSF

Executive Summary

The time domain of the sky has been only sparsely explored. Nevertheless, recent discoveries from limited surveys and serendipitous discoveries indicate that there is much to be found on timescales from nanoseconds to years and at wavelengths from meters to millimeters. These observations have revealed unexpected phenonmena such as rotating radio transients and coherent pulses from brown dwarfs. Additionally, archival studies have found not-yet identified radio transients without optical or high-energy hosts. In addition to the known classes of radio transients, possible other classes of objects include extrapolations from known clases and exotica such as orphan γ-ray burst afterglows, radio supernovae, tidally-disrupted stars, flare stars, magnetars, and transmissions from extraterrestrial civilizations.

Over the next decade, meter- and centimeter-wave radio telescopes with improved sensitivity, wider fields of view, and flexible digital signal processing will be able to explore radio transient parameter space more comprehensively and systematically.

1 Frontier Question: What New Sources and Phenomena Populate the Sky?

The available parameter space for transient surveys is extensive: transients have been detected at, and are predicted for, all radio wavelengths; timescales range from nanoseconds to the longest timescales probed; and transients may originate from nearly all astrophysical environments including the solar system, star-forming regions, the Galactic center, and other galaxies.

By observing the sky so as to preserve information about the time domain, the past decade has illustrated that there is a considerable potential for discovery. Over the next decade, a combination of increased sensitivity, field of view, and algorithmic developments likely would yield transformational discoveries in a wide range of astronomical fields.

2 Science Opportunity: The Dynamic Sky

Transient emission—bursts, flares, and pulses on time scales of less than about 1 month—marks compact sources or the locations of explosive or dynamic events. Transient sources offer insight into a variety of fundamental questions including

- Mechanisms of particle acceleration;
- Possible physics beyond the Standard Model;
- The physics of accretion and outflow;
- Stellar evolution and death;
- The nature of strong field gravity;
- The nuclear equation of state;
- The cosmological star formation history;
- Probing the intervening medium(a); and
- The possibility of extraterrestrial (ET) civilizations.

Much of astronomy's progress over the last half of the $20^{\rm th}$ Century resulted from opening new spectral windows. With essentially the entire spectrum having been explored at some level, we must look to other parts of parameter space—such as increased sensitivity, field of view, or the time domain—for future transformational discoveries.

The time domain appears ripe for new exploration as observations over the past decade have emphasized that the sky may be quite dynamic—known sources have been discovered to behave

Table 1: Illustrations of Classes of Transients

Known Classes	**Extrapolations of Known Physics**	**Exotica**
brown dwarfs, flare stars	extrasolar planets	signals from ET civilizations
pulsar giant pulses, intermittant pulsars, magnetar flares, X-ray binaries	giant pulses, flares from neutron stars in other galaxies	electromagnetic counterparts to gravitational wave events
radio supernovae, GRB afterglows	prompt emission from GRBs, orphan GRB afterglows	annihilating black holes
variability from interstellar propagation	variability from intergalactic propagation	

in new ways and what may be entirely new classes of sources have been discovered. Radio observations triggered by high-energy observations (e.g., observations of γ-ray burst [GRB] 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, brown dwarfs) all suggest that the sky is likely to be quite active on timescales from nanoseconds to years and at wavelengths from meters to millimeters.

3 Scientific Context: The Transient Sky

Classes of transients are diverse, ranging from nearby stars to cosmological distances (GRBs), and touching upon nearly every aspect of astronomy, astrophysics, and astrobiology. Table 1 lists a series of known, hypothesized, and exotic classes of radio transients. In the remainder of this section, we provide two case studies and brief discussions of other classes of transients.

3.1 Case Study: Rotating Radio Transients—A New Population of Neutron Stars

The first pulsars were discovered through visual inspection of pen chart recordings, which revealed the presence of individual radio pulses spaced by the neutron star rotation period. It was soon realized that Fourier methods were far more sensitive to the periodic emission believed to be characteristic of all radio pulsars, and periodicity searches have been used in the discovery of over 1800 radio pulsars.

In 2003, the Parkes Multibeam Survey had covered the entire Galactic plane visible from Parkes, finding over 700 new pulsars. The data were then re-analyzed for single, dispersed pulses, revealing a new population of neutron stars only detectable through their individual radio bursts (McLaughlin et al. 2006). The average pulse rates of these 11 sources were $(3\ \mathrm{min})^{-1}$ to $(3\ \mathrm{hr})^{-1}$. Periods ranging from 0.7–7 s were eventually inferred from the differences between the pulse arrival times. These periods are comparable to those of traditional radio pulsars, and confirmed the neutron star nature of these sources, dubbed Rotating Radio Transients (RRATs).

Since the discovery of the original 11 RRATs, interest in single radio pulse searches has increased dramatically. Single pulse searches are incorporated in the pipeline of current pulsar surveys,

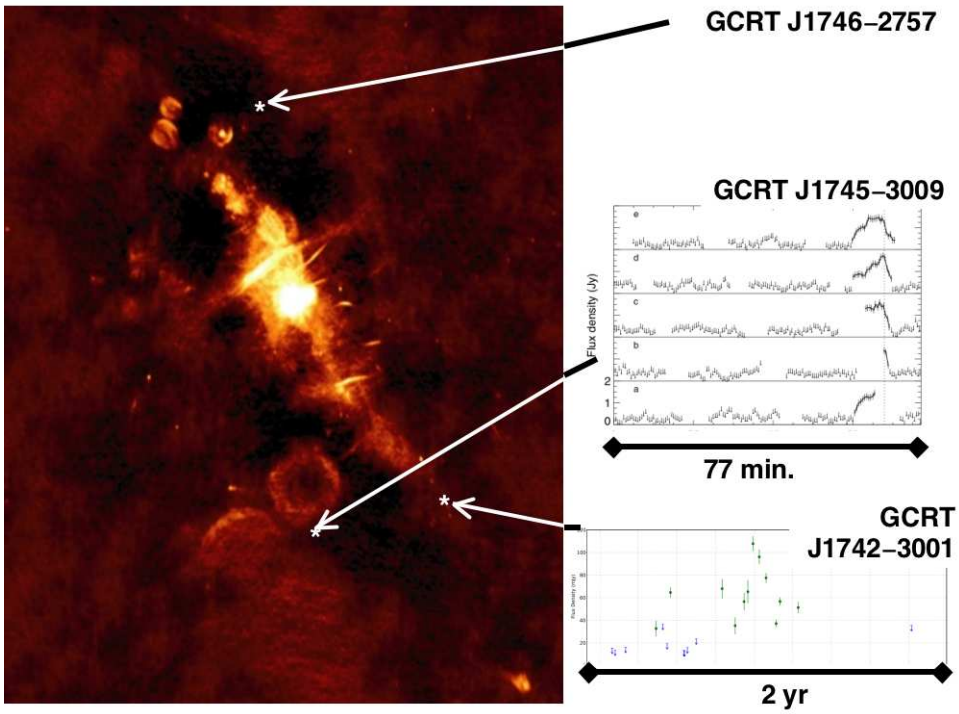

Figure 1: Illustration of the diversity of the light curves for transients toward the Galactic center (Hyman et al. 2002, 2005, 2009). The transient GCRT J1745−3009 burst several times (duration $\sim$ 10 min.) during a 6-hr observation, with subsequent bursts detected over the next 1.5 yr; GCRT J1742−3001 brightened and faded over several months, preceded 6 months earlier by intermittent bursts; and GCRT J1746−2757 was detected in only a single epoch. None of these objects has been identified nor has a multi-wavelength counterpart been found. The background image is the Galactic center at 330 MHz, and the total time devoted to the monitoring project, in both new and archival observations, is about 150 hr.

and a great deal of archival pulsar search data has been reanalyzed. Currently, roughly 30 RRATs are known, with this number increasing steadily.

What makes RRATs so different from normal pulsars, and how might they be related to other classes of neutron stars? Perhaps fundamental properties such as magnetic field or age contribute to the radio sporadicity, or their emission could be due to external influences such as a debris disk (Cordes & Shannon 2008). Another fundamental issue is the total number of these sources. Their sporadicity makes them difficult to detect, and it is likely that the population of RRATs outnumbers that of normal pulsars, leading Keane & Kramer (2008) to conclude that the neutron star population is *not* consistent with the Galactic supernova rate.

In summary, the RRATs are an example of an unexpected source class discovered through simple but new transient detection algorithms.

3.2 Case Study: Unexplained Transient Events

Figures 1 and 2 illustrate the potential diversity of objects to be discovered. These transients were discovered in a combination of new and archival observations toward the Galactic center (Figure 1) or in archival observations of a "blank field" (Figure 2). Archival data have proven

particularly valuable resources for these programs as both span 1–2 decades of time. Most of the transients shown in these figures have no multi-wavelength counterparts, nor are they associated with any known transient classes. Possible explanations for the various transients range from rare, extremely luminous flares from Galactic M dwarfs and brown dwarfs to GRB afterglows.

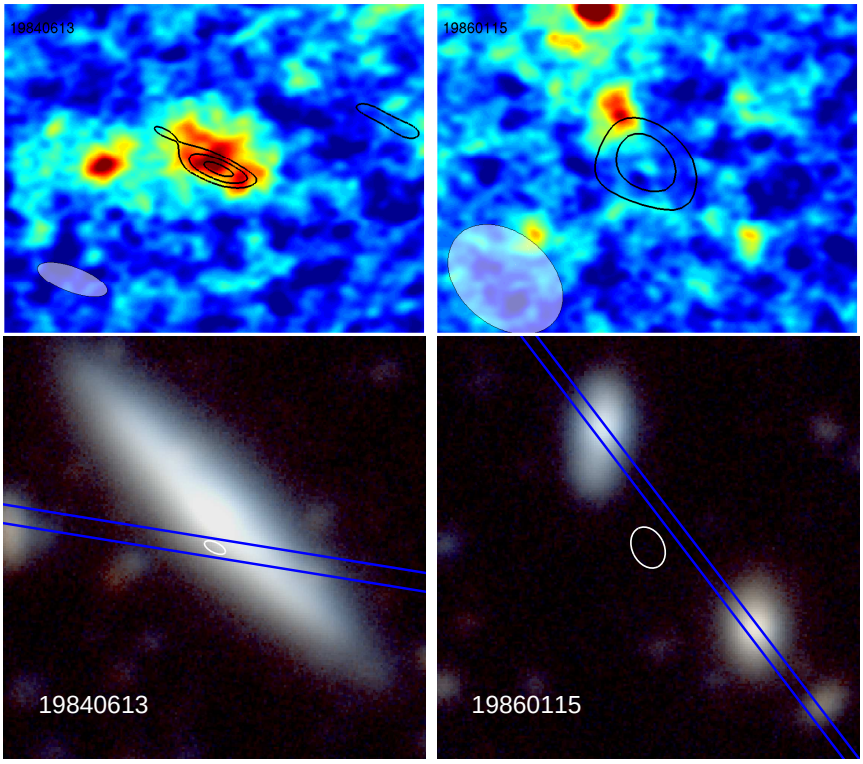

Figure 2: Two radio transients found in a survey of 944 epochs of a blank field from the VLA archives (Bower et al. 2007); there is no clear object class identification for these or eight other transients. (*Top*) Contours indicate the transients' locations on the deep radio image. (*Bottom*) The positions of the radio transients overlaid on deep Keck G and R band images. RT 19840613 is offset by 3 kpc from the nucleus of a spiral galaxy at $z = 0.04$; RT 19860115 has no radio or optical counterpart.

3.3 Diverse Populations: Opportunity for Discovery

Flare Stars, Brown Dwarfs, and Extrasolar Planets: Active stars and star systems have long been known to produce radio flares attributed to particle acceleration from magnetic field activity (Güdel 2002). More recently, flares from late-type stars (dM) and brown dwarfs have been discovered (Berger et al. 2001; Hallinan et al. 2007), in some cases with periodicities indicative of rotation. The radio emission from these late-type stellar objects is far stronger than expected from the Benz-Güdel relation for X-ray and radio emission from main-sequence stars. Finally, Jupiter is radio bright below 40 MHz, and many stars with "hot Jupiters" show signatures of magnetic star-planet interactions (Shkolnik et al. 2005), so extrasolar planets may also be radio sources (Zarka 2007).

Pulsar Giant Pulses—Relativistic Magnetohydymamics and the Intergalactic Medium: While all pulsars show pulse-to-pulse intensity variations, some pulsars emit so-called "giant" pulses, with strengths 100 or even 1000 times the mean pulse intensity. The Crab was the first pulsar found to exhibit this phenomenon, and giant pulses have since been detected from numerous other pulsars (Cognard et al. 1996; Romani & Johnston 2001; Johnston & Romani

2003). Pulses with flux densities of order 10^3 Jy at 5 GHz and with durations of only 2 ns have been detected from the Crab (Hankins et al. 2003). These "nano-giant" pulses imply brightness temperatures of 10^{38} K, by far the most luminous emission from any astronomical object. In addition to being probes of particle acceleration in the pulsar magnetosphere, giant pulses may serve as probes of the local intergalactic medium (McLaughlin & Cordes 2003).

Radio Supernovae and GRBs: Observations of the kind possible with the new radio telescopes (i.e., frequent monitoring of large areas of sky) can be used to find those GRBs and supernovae that emit in the radio, as well as to follow up on such transients detected at other wavelengths. Multi-wavelength, multi-epoch observations (e.g., Cenko et al. 2006) can provide information on progenitors, the surrounding medium, and models of GRB energetics and beaming. Of special interest is finding so-called "orphan afterglows," those without γ-ray trigger. The demographics of orphan afterglows directly inform the geometry and hence energetics of the events (e.g., Levinson et al. 2002).

Intraday Variability, AGN Central Engines, and Interstellar & Intergalactic Media: Intraday variability (IDV)—interstellar scintillation of extremely compact components ($\sim$ 10 μas) in AGN—occurs at frequencies near 5 GHz. The typical modulation amplitude is a few percent, but occasional sources display much larger modulations (Kedziora-Chudczer et al. 2001; Lovell et al. 2003); in *extreme scattering events*, modulations greater than 50% on time scales of days to months are obtained (Fielder et al. 1987). The existence of compact components in AGN may prove to be a sensitive probe of their central engines, innermost regions of the jet, or both, complementing γ-ray observations. Finally, in order for AGN to be sufficiently compact to scintillate, their signals must not have been affected substantially by propagation through the *intergalactic medium*. Given that the dominant baryonic component of the Universe is likely to be in a warm-hot intergalactic medium, the presence of IDV can also constrain the properties of the intergalactic medium.

Annihilating Black Holes: Annihilating black holes are predicted to produce radio bursts (Rees 1977). Advances in γ-ray detectors has renewed interest in possible high-energy signatures from primordial black holes (Dingus et al. 2002; Linton et al. 2006). Observations at the extremes of the electromagnetic spectrum are complementary as radio observations attempt to detect the pulse from an individual primordial black hole, while high-energy observations generally search for the integrated emission.

Gravitational Wave Events: The progenitors for gravitational wave events may generate associated electromagnetic signals or pulses. For example, the in-spiral of a binary neutron star system, one of the key targets for LIGO, may produce electromagnetic pulses, both at high energies and in the radio due to the interaction of the magnetospheres of the neutron stars (e.g., Hansen & Lyutikov 2001). More generally, the combined detection of both electomagnetic and gravitational wave signals may be required to produce localizations and understanding of the gravitational wave emitters (Kocsis et al. 2008). See also the whitepaper on the GW-EM connection (Bloom et al. 2009).

Extraterrestrial transmitters: While none are known, searches for extraterrestrial intelligence (SETI) have found non-repeating signals that are otherwise consistent with the expected signal from an ET transmitter. Cordes et al. (1997) show how ET signals could appear transient, even if intrinsically steady.

4 Advancing the Science: Exploring Phase Space

Over the next decade, great progress is possible in the study of transients. Specific steps include (1) Explicit time-domain processing of data coupled with algorithmic developments, particularly in the area of identification and classification of transients; and (2) Exploitation of telescopes with higher sensitivities, wider fields of view, or both.

The transient detection figure of merit at radio wavelengths is

$$\mathrm{FoM}_t = \Omega \left(\frac{A_{\mathrm{eff}}}{T_{\mathrm{sys}}} \right)^2 K(\eta W, \tau W), \tag{1}$$

which is a function of the telescope sensitivity $A_{\mathrm{eff}}/T_{\mathrm{sys}}$, instantaneous solid angle Ω, typical time duration of the transient W, event rate η, and the time per telescope pointing ("dwell time") τ. The function $K(\eta W, \tau W)$ incorporates the likelihood of detecting a particular kind of transient. Roughly, one can separate transients surveys into two classes: (1) Burst searches that probe timescales of less than about 1 s for which Ω is large but $A_{\mathrm{eff}}/T_{\mathrm{sys}}$ is small; and (2) Imaging surveys conducted with interferometers that typically probe timescales of tens of seconds and longer and for which Ω is small but $A_{\mathrm{eff}}/T_{\mathrm{sys}}$ is large.

1. **Explicit time-domain processing of data and algorithmic developments:** Since the discovery of RRATs, interest in single radio pulse searches has increased dramatically. Searches for single, dispersed pulses now are incorporated in the software pipeline of current pulsar surveys, such as those at Arecibo, the GBT, and Parkes, and archival pulsar data have been reanalyzed. While time-domain processing is not yet standard for many interferometers, the ASKAP, ATA, EVLA, LOFAR, LWA, MWA, and eventually the SKA offer new possibilities for expanding time-domain processing to interferometric imaging. Further, the interferometers offer the possibility of much higher positional information for transients, which is essential for multi-wavelength study.

   A number of algorithmic improvements would yield improved use of the existing telescopes and likely a higher yield from future telescopes.

   - The vast storage and computational requirements of transient searches, particularly in the case of imaging interferometers, requires the development of near real-time transient analysis pipelines. The ATA, LOFAR, and MWA projects are all engaged in the development of such first-generation pipelines.
   - The identification, avoidance, and excision of radio frequency interference (RFI) produced by civil or military transmitters operating in the radio spectrum is required. These transmitters are often orders of magnitude stronger than the desired astronomical signal.
   - The identification and classification of transients is a challenge that is broader than simply radio wavelength transients.

2. **Exploitation of telescopes with higher sensitivities, wider fields of view:** Generally, both $A_{\mathrm{eff}}/T_{\mathrm{sys}}$ and Ω should be large, though depending upon the class of transient and its luminosity function (if known), it may be possible to trade $A_{\mathrm{eff}}/T_{\mathrm{sys}}$ vs. Ω. For instance, X- and γ-ray instruments with large solid angle coverage and high time resolution have had great success in finding transients, even if the detectors were not particularly sensitive.

In the last decade, the field of view of the Arecibo telescope around 1 GHz was expanded by a factor of 7 with a new feed system (ALFA). In the next decade, additional field of view expansion technologies such as *phased-array feeds* offer the potential of expanding the fields of view of single-dish telescopes such as Arecibo and the GBT by factors of 10 or more.

For imaging surveys, LOFAR, the LWA and the MWA promise much higher sensitivities at low radio frequencies for which the fields of view are naturally large (~ 10 deg.^{2}). The ASKAP and ATA both offer the promise of much larger fields of view (~ 10 deg.^{2}) at frequencies near 1 GHz, while the EVLA will provide a factor of 10 in sensitivity improvements across its entire operational range (1–50 GHz). All of these imaging interferometers also can be *sub-arrayed*, providing improvements in field of view (~ 100 deg.^{2}), at the cost of sensitivity.

Looking toward the next decade and to the era of the SKA, the above advances in searches for transient radio sources promise to transform our understanding of the dynamic Universe.

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