

Chapter 3 The Dynamic Radio Sky: Slow Transients

Summary: Slow Transients

Authors: Anna Y. Q. Ho (Cornell University; on behalf of the SAC)

The dynamic sky on timescales from days to years is only just beginning to be explored at radio wavelengths. In the past few years, a variety of transients have been discovered using VLA Sky Survey data, some of which may represent long-sought events (e.g., off-axis γ -ray burst afterglows, pulsar wind nebulae) and some of which may represent new and unexpected phenomena (e.g., the merger of a compact object and a massive star). The results from the past few years represent the tip of the iceberg of what will be revealed by the DSA-2000's unprecedented depth (Section 2.1), and discoveries will benefit from machine learning classification and anomaly detection tools (Section 2.4).

One major theme in the following sections is the scientific benefit of an all-sky survey, which mitigates the selection bias inherent in targeted radio observations. DSA-2000 can reveal the statistics of radio emission in stellar explosions (supernovae; Section 2.3); magnetic flaring activity in low-mass stars (Section 2.7); and relativistic jetted phenomena such as tidal disruption events (Sections 2.1, 2.6), γ -ray bursts, and luminous fast blue optical transients (Sections 2.1, 2.7).

Another theme is the benefit of having DSA-2000 radio coverage overlapping with major surveys at other bands, including ongoing (e.g., ASAS-SN, ATLAS, ZTF) and future (the Vera Rubin Observatory's Large Synoptic Survey Telescope, LS4) optical surveys. The overlap between DSA-2000 and LSST fields will enable studies of hot magnetic stars through their electron cyclotron maser emission (Section 2.2). In addition, the DSA-2000 coverage of the large numbers of supernovae discovered and classified by optical surveys (today the rate is approximately one per night) will enable large-scale systematic studies of supernova radio emission, which in turn gives insight into their progenitor channels and the role of binarity (Section 2.3). Interpreting DSA-2000 radio observations of relativistic transients requires overlap with surveys at other wavelengths, particularly high-energy (γ -ray, X-ray).

Finally, an additional recurring theme is that significant scientific advances in a variety of topics would be enabled by adopting a wider variety of cadences, some faster (one every few days) and some slower, than the nominal one per four months plan. These topics include very early rapidly evolving emission from supernovae, which may be the key to understanding the link between γ -ray bursts and “normal” stellar explosions (Section 2.5); mysterious flares from tidal disruption events (Section 2.6) which may be related to the intermittent activity of a relativistic jet; and relativistic stellar explosions (the afterglows and cocoons of γ -ray bursts, and the mysterious “luminous fast blue optical transients” such as AT2018cow; Section 2.7).

3.1 The Dynamic Radio Sky in Unprecedented Depth

Authors: Dillon Z. Dong

Summary

The planned DSA 2000 Cadenced All Sky Survey (CASS) will obtain a ~ 4 month cadence lightcurve over 16 epochs for every ~ 1 GHz source brighter than a few μJy in the northern sky. The $\sim 2000 \text{ deg}^2$ pulsar timing and $\sim 30 \text{ deg}^2$ deep-drilling fields will sample smaller portions of the sky on faster timescales to similar per-epoch depths (and factors of a few deeper when stacked). Due to the large volume probed, CASS will dramatically increase the sample size of known transient classes, such as supernovae, gamma ray bursts, AGN outflows, tidal disruption events, flares from stars and compact objects. The pulsar timing and deep-drilling surveys will allow us to identify a subset of transients that evolve on faster timescales, including intrinsically lower-luminosity non-terminal transients from stellar-mass objects, as well as relativistic outflows. Each of the surveys will open the door for the serendipitous discovery of new transient classes which are inaccessible to present-day surveys due to their rarity. When combined with the diagnostic power of contextual data from multi-wavelength surveys (both time-domain and single epoch), the DSA 2000 will revolutionize our understanding of the dynamic radio sky.

State of the Field

Radio transients provide a window into the ever-changing behavior of universe’s relativistic particle accelerators. These ephemeral sources allow us to measure properties of the universe on angular scales smaller than milliarcseconds to microarcseconds, probing phenomena that are impractical to observe at scale (or impossible to observe at all) in any other way. To date, most of our knowledge of radio transients (aside from fast transients on timescales of $\sim$ milliseconds to hours such as fast radio bursts and stellar flares) has come from follow-up observations of transients first discovered at other wavelengths. Though follow-up detections yield valuable insights, they are fundamentally biased, as they require not only an early multiwavelength counterpart (which may not exist for some radio transient classes), but also a subjective decision to take a follow up observation. These biases can be addressed by searching for radio transients directly in radio surveys.

Over the past few decades, many surveys of ever increasing sensitivity and areal coverage have steadily increased our ability to detect radio transients without the need for prior detections at other wavelengths (see e.g., fig 2. of Lacy et al. 2020 for a summary). In the mid 2010s, the Caltech NRAO Stripe 82 Survey (CNSS; Mooley et al. 2016) finally reached a scale where transients are consistently being detected uncovering $\mathcal{O}(10)$ transients in a search of 300 deg^2 at 3 GHz to a typical RMS of $\sim 80 \mu\text{Jy}$ (e.g., Anderson et al. 2019, Wolowska et al. 2021). This success helped motivate the VLA Sky Survey, which is using the same techniques to observe the entire 3 GHz northern sky ($\sim 30,000 \text{ deg}^2$) to a depth of $\sim 140 \mu\text{Jy}$ (Lacy et al. 2020). In preliminary work, we have found that VLASS contains $\mathcal{O}(10^3)$ transients per epoch, a scale where direct detections now outnumber follow-up detections for the first time (Dong et al. 2023, in prep). This order-of-magnitude increase in scale has paved the way for both statistical samples of known transient classes and the discovery of new ones. Examples include a population of new jets launched from quasars (Nyland et al. 2020), a wide diversity of tidal disruption events (Somalwar et al. 2021, 2022, 2023abc in prep) and flaring stars (Ayala et al. 2023 in prep), a stellar explosion driven by the merger of a compact object and a massive star (Dong et al. 2021), and the emergence of an extremely energetic new pulsar wind nebula (Dong & Hallinan 2023).

A number of other radio transient searches are also demonstrating that the sky is active at lower frequencies than VLASS. Though the LOTSS survey (a LOFAR 140 MHz survey reaching a depth of $95\mu\text{Jy}$; Shimwell et al. 2017, 2022) is not designed as a time-domain experiment, it is possible to reprocess the data to search for time variable phenomena. The first results have come in the form of candidate star-planet interactions (Vedantham et al. 2020, Callingham et al. 2021). The ASKAP/VAST survey (Murphy et al. 2013) is specifically designed as a time-domain survey that will produce 888 MHz lightcurves over a $\sim 10,000\text{ deg}^2$ area at a depth of $\sim 100 - 200\mu\text{Jy}$. A number of results have been released thus far, including the discovery of highly polarized emission from 33 stars (Pritchard et al. 2021), and an as-yet unidentified transient within 4 degrees of the Galactic center (Wang et al. 2021). The ThunderKAT survey is searching for transients commensally with other MeerKAT surveys and has found a number of Galactic transients, along with the discovery of a radio-luminous neutron star with an ultra-long rotation period of 76s (Caleb et al. 2022). All of the above surveys are in their initial stages, and can reasonably be expected to continue the stream of new radio transient discoveries in the next few years.

DSA-2000's impact

The DSA 2000 CASS will be ~ 2 orders of magnitude deeper than the present-day time-domain radio surveys described above, so it should be sensitive to transients in a volume ~ 3 orders of magnitude larger. With this increase in scale, we will be sensitive to a sizable new parameter space, which may contain new transient populations that are too rare to be detectable in current surveys. The sample size of currently known transient classes should also go up in proportion to the volume, provided that we are able to identify them as such. This identification will be aided by the increase in contextual information from current and near-future sky surveys (e.g., the Rubin LSST, DESI, Roman, SPHEREx). Additionally, the DSA 2000 will provide its own context in many cases, through polarization measurements and the detection of radio recombination lines and the 21cm line (providing a redshift for extragalactic transients), and through the availability of lightcurves to measure the rise and fade time of transients. In order to interpret these lightcurves it will be essential to develop robust difference imaging techniques, methods to sharpen the localization of point sources in the presence of diffuse emission, and to understand both the quiescent and variable emission from radio sources that will become detectable at $\sim 500\text{ nJy}$ depths. In addition to aiding in transient detection, this work will be scientifically fruitful for a number of fields. For instance, the vast population of scintillating radio sources can be used to map out the structure and turbulent fluctuations of the Galactic ISM. Finally, the deep all-sky image produced by CASS will serve as a reference epoch for any future $\sim 1\text{ GHz}$ observations (e.g. with the ngVLA), providing a boon to direct radio transient detection far into the future.

System requirements / desired additions to baseline design (see table below)

The DSA 2000's baseline design is already well-suited for transient searches. However, there are a few modifications that we believe could substantially increase the scientific return. First, we suggest that the various surveys be observed in a way that provides significant coverage at a wide range of cadences (potentially logarithmically spaced). In CASS, this could be accomplished by observing fields out of order, while in the deep fields, we suggest grouping observations in a few bursts (to facilitate searches for longer timescale transients in stacked observations). Spacing epochs in this way will provide crucial diagnostic information for distinguishing fast-evolving transients from slower ones. This information can in turn be used to aid in multi-wavelength cross matching (since emitting regions of smaller physical

size / lower luminosity will tend to evolve faster; Pietka et al. 2015). We particularly suggest that faster timescale epochs be observed in the Galactic plane. Second, if it is possible, we suggest that outriggers be built so that selected sources can be localized with higher precision. Current radio transient surveys are already encountering issues with false association probabilities. While DSA 2000 transients will have much better contextual information and will in some cases provide their own context, the number of transients that can be associated with multi-wavelength counterparts is still expected to be limited by the limited resolution and the sheer number of transients expected.

Table 3.1: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Spatial resolution	3.5"	Ideally as fine as possible (with outriggers)
Cadence	1 every 4 months	Ideally varied

3.2 Systematically characterizing the binarity in stripped envelope supernovae progenitors

Authors: Poonam Chandra

Summary

Prior to explosion of a massive star as a supernova, stripping of mass from the outer layers of the star leads to varying amount of hydrogen and/or helium at the time of supernova explosion. Type IIb (very small amount of hydrogen), Type Ib SNe (absence of hydrogen) and Type Ic SNe (absence of hydrogen and helium) are collectively called stripped-envelope supernovae (SESNe), and they together form a continuum with increasing amount of mass stripping of the progenitor star. Mechanism of stripping mass in SESNe is not clear, though consensus currently is that single stars may not be able to lose all of their H/He envelope and binarity may be important (Meynet and Maeder 2005; Eldridge and Vink 2006). In some cases archival images have shown surviving companion of the supernova progenitor star (Gilkis and Arcavi 2022; Kilpatrick et al. 2021; Arcavi et al. 2017a). However, these images only reflect the time stamp evidence of a binary companion, the evolution under the influence of binary and the binary separation are not possible to determine via these images. The binary companion's interaction with supernova progenitor is likely to result in enhanced mass-loss and asymmetric, shell like or complex circumstellar medium, which can be best probed via radio bands. In some cases late time enhanced radio emission has been seen and has indicated the signatures of binary progenitors in some SESNe (Chandra et al. 2020; Bietenholz and Bartel 2017b; Stroh et al. 2021a; Maeda et al. 2023). Radio observations revealing late time enhancements is the best way to probe the evidence of binary companion and its effect on the supernova progenitor evolution, however, unpredictable due to uncertainty in binary separation and the resulting interaction. As described below, DSA2000 has potential to systematically characterize the binarity in SESNe.

State of the Field

Late time radio enhancements in SESNe have been seen on a timescale of a few months (e.g. SN 2014C, Margutti et al. 2017b; SN 2018ivc, Maeda et al. 2023), to a few years (e.g. SN 2001em, Chugai and Chevalier 2006) to decades (e.g. SN 2001em, Chandra et al. 2020; SN 1986J, Bietenholz and Bartel 2017b). Recently Stroh et al. 2021a revealed late time radio enhancements in 19 supernovae 1–60 years of age during VLASS first epoch observations. Thus it appears that the late time radio enhancements can be seen at unpredictable epochs. This uncertainty comes because epoch of radio enhancements due to dense circumstellar components created due to binarity greatly depends on the binary separation and the post binary interaction mass-loss rate. However, both are extremely difficult to predict. Ideally one needs to keep observing SESNe for several decades with a log cadence, which is highly impractical and demands unrealistic telescopes' time. This has obviously not been possible and hence it has not been possible to conclusively indicate the role of binary companion in SESNe.

DSA-2000's impact

DSA2000 will survey the northern sky covering 30,000 sq-deg 16 times over the span of 5 years with a sensitivity of 2 μ Jy/beam per epoch. It is likely to cover hundreds if not thousands of stripped envelope supernovae at varied time scales and may reveal radio enhancements at different epochs. These time

scales will correspond to thousands of years before the supernova explosion and thus will systematically characterize the binarity in supernovae progenitors of stripped envelope supernovae.

System requirements / desired additions to baseline design

N/A

3.3 Fast Radio Supernovae

Authors: Assaf Horesh

Summary

While in some supernovae (SNe) the radio emission at low GHz frequencies evolves relatively slowly, some other SNe exhibit fast evolving radio emission. An example of such "fast" radio SNe is a sub type of Type Ic SNe, which may be the missing link between normal Type Ic SNe and relativistic ones. So far only a handful of such SNe have been discovered as they exhibit lower peak fluxes than normal Type Ic SNe and their radio emission fades away within a couple of weeks. DSA-2000 with its enhanced sensitivity can open up a window for probing this unexplored phase space of fast radio SNe, but it requires that the DSA-2000 will devote some of its observing time for high cadence observations.

State of the Field

Radio observations of supernovae (SNe) and other types of transient phenomena have been providing diagnostics not accessible in other wavelengths, over the last few decades. These diagnostics include: calorimetry, measuring outflow velocities and their temporal evolution, and mapping the circumstellar material (CSM) around SN progenitors (and hence tracing their mass-loss histories). This type of diagnostics have been employed also on stripped envelope supernovae.

Stripped envelope SNe are believed to originate from progenitor stars that have been stripped of most of their Hydrogen (Type Ib) and sometimes also of their Helium (Type Ic) envelopes. Radio observations are in good accord with the above description. As an example, in the case of PTF 13bvn (Cao, Kulkarni, Horesh et al. 2013), the radio analysis is consistent with the progenitor being a stripped compact Wolf-Rayet star. This matches the properties of the optical progenitor that have been identified, for the first time in the case of a Type Ib SN, in archival optical images. Radio observations of PTF 13bvn and other normal Type Ib/c SNe (e.g., SN 1994I, SN 2004cc) show that the fastest outflows from ordinary Type Ib/c SNe have velocities of $\sim 0.1 c$.

Radio diagnostics came to the fore also for stripped envelope supernovae associated with Gamma Ray Bursts (GRBs). The first example was SN 1998bw (a broad-lined Type Ic; Ic-BL), associated with the nearby, low-luminosity gamma-ray burst GRB 980425 (Galama et al. 1998). Radio observations established that the fastest moving ejecta were mildly relativistic and carried a significant amount of the explosion energy (Kulkarni et al. 1998). The same approach showed that SN 2009bb (Type Ic-BL) also had mildly relativistic ejecta and it has been reasonably argued that either SN 2009bb did not produce gamma-rays or that the associated GRB was likely not pointed towards us (or we missed detecting the gamma-rays; Soderberg et al. 2010). It is worth noting that in both cases the optical line features were very broad, i.e., $\approx 0.1 c$.

It turns out that Type Ic SNe with intermediate velocities (fast but not relativistic) do exist, but this population remained so far mostly unexplored. In the past, there have been only 3 cases of "fast" radio SNe where Type Ib/c SNe have exhibited outflows with velocities that are in the range between ordinary and relativistic SNe Ib/c. A relatively recent example is PTF 12gzk, discovered by the Palomar Transient Factory (PTF) a few days after explosion at 58 Mpc (Ben-Ami et al., 2012). The initial optical spectra exhibited high-velocity (but not broad) lines with velocities of $\sim 35,000 \text{ km s}^{-1}$. Our radio observations at 6 GHz of PTF 12gzk, 8 days after explosion revealed a fast fading radio emission (Horesh et al. 2013). This means that the radio emission optical depth has already dropped to low GHz frequencies early on. The radio emission became too faint to detect 10 days after explosion. As we showed in Horesh et al. (2013), the SN ejecta was expanding at high velocity of $\sim 0.3 c$,

a higher velocity than observed in ordinary SNe Ibc (see Figure 3.1). The radio data also indicated that the density of the CSM around the supernova is lower by a factor of ~ 10 than the CSM density around normal Type Ibc SNe.

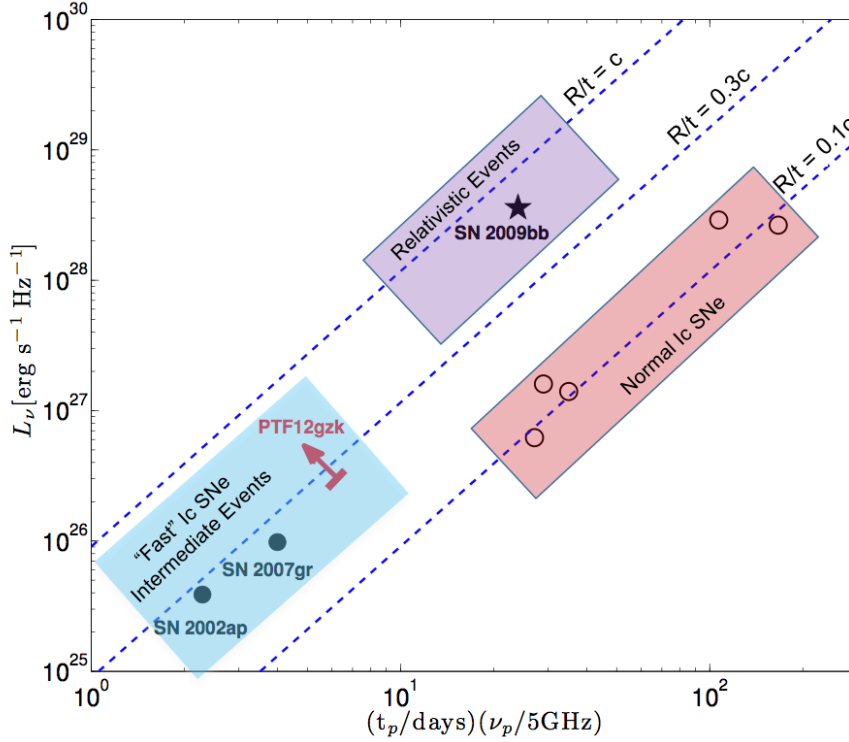


Figure 3.1: Chevalier luminosity-peak time diagram. The open black circles are measurements (selection of a few) of the “ordinary” (with radio emission peaking at low frequencies on timescales of weeks) Ic SNe. The 5-GHz luminosity of PTF 12gzk is already decaying 8 days after explosion. Therefore, the peak time is ≤ 7 days. From this we concluded that PTF 12gzk is a high speed Ic supernova with mean ejecta velocity (of the leading edge) in excess of $80,000 \text{ km s}^{-1}$ (Horesh et al. 2013). PTF 12gzk together with only SN 2007gr and SN 2002ap represent the poorly explored population of intermediate Type Ic SNe ($0.2 - 0.3 c$ in velocity space; shaded blue area), between normal ones (up to $0.1 c$; shaded red) and relativistic ones (shaded purple). These SNe also seem to have very different CSM environment leading to only weak radio emission.

PTF 12gzk, however, is not the first of its kind (fast fading radio SNe, with intermediate shockwave velocities). In the past, SN 2002ap (Berger et al. 2002) and SN 2007gr (Soderberg et al. 2010) showed similar characteristics. The difference is that both of these SNe were detected in the radio within 10 Mpc, using old radio facilities while the radio emission from PTF 12gzk was detected at a distance of 58 Mpc using newly upgraded facilities. Both SN 2002ap and SN 2007gr had radio emission that evolved relatively fast, with SN 2002ap peaking at $t \approx 2 - 3$ days (4.86 GHz) and SN 2007gr peaking at $t \approx 3 - 4$ days (8.46 GHz), after explosion. The radio analysis by both Berger et al. (2002) and Soderberg et al. (2010) suggests shockwave velocities of $0.2 - 0.3 c$ traveling in low-density CSM environments, similar to PTF 12gzk.

The above “fast” evolving radio events (i.e., SNe with weak radio emission peaking in the low GHz range only a few days after explosion and quickly fading) may represent the population of a missing link between ordinary and relativistic Type Ib/c SNe. DSA-2000, can possibly expand the detection horizon of such events and thus significantly boost the number to detected SNe of this type.

DSA-2000's impact

At less than a 100 Mpc, fast radio SNe seem to exhibit peak fluxes of a few tens of μJy . The enhanced sensitivity of the DSA-2000 will therefore increase the chances for discovering a growing number of such events. An attempt to carry out a survey to search for such events, may reveal a large population of events that remained unexplored so far.

System requirements / desired additions to baseline design (see table below)

In order to detect fast radio SNe, one has to carry out a high-cadence survey with a cadence of 3-4 days. It is therefore worth while to consider whether such an observing strategy can be implemented in the DSA-2000.

Table 3.2: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Cadence	1 every 4 months	Requires a cadence of 3-4 days

3.4 Characterizing the coherent radio emission from magnetic massive stars

Authors: Poonam Chandra & Barnali Das

Summary

Electron cyclotron maser emission (ECME) is a highly circularly polarized coherent emission, produced by mildly relativistic electrons with an unstable energy distribution, provided the local electron gyrofrequency is larger than the corresponding plasma frequency. ECME from a hot magnetic star was first discovered in 2000 (Trigilio et al. 2000). Since then, several other hot magnetic stars have been found to produce ECME (e.g. Chandra et al. 2015; Leto et al. 2019; Das et al. 2022 etc.), and it has recently been speculated that this phenomenon might be ubiquitous amongst the hot magnetic stars population (Das et al. 2022). To describe these stars, Das and Chandra 2021 introduced the term ‘Main-sequence Radio Pulse emitter’ (MRP). The distinctive characteristic of MRPs is the exhibition of a pair of oppositely circularly polarized radio pulses (produced by ECME) encompassing the magnetic nulls (the rotational phases when the stellar longitudinal magnetic field is zero) over a certain ranges of frequencies, typically up to a few GHz. This is a newly evolving field with potential applications to other contemporary fields such as coherent radio emission from ultra-cool dwarfs, brown dwarfs, and even exoplanet detection via star-planet interaction. The advantage of MRPs over other objects emitting ECME is that their magnetic fields are stable throughout their lifetimes, and also extremely well-characterized. However, to achieve these milestones, it is essential to fully understand the ECME phenomenon, and this process is currently at its infancy. As described below, DSA-2000 has huge potential to drastically transform this field.

State of the Field

Currently more than a dozen MRPs are known to emit ECME. While only one such star was known until the year 2015, this is still a very small sample size to infer the statistical properties of these objects. As ECME theoretically originates at magnetic nulls in the MRPs, the observations towards ECME search usually cover only magnetic stars with short rotation periods and around their magnetic nulls due to limited observing time available (Das et al. 2022). In the past this may have resulted in missing some MRPs showing ECME shifted from nulls due to propagation effects (Das, Mondal, and Chandra 2020), or from the long rotation period MRPs.

In addition, due to limited observational time on known MRPs, detailed understanding of their nature remains largely unknown. Whenever a MRP has been observed in detail, it has revealed surprises. For example, we have seen stellar orientation dependence of ECME properties (e.g. HD 133880, Das, Chandra, and Wade 2020), dramatically different spectra for right and left circularly polarized ECME (CU Vir, Das and Chandra 2021); both characteristics potentially reflecting the non-azimuthally symmetric plasma distribution in stellar magnetospheres. We have also witnessed transient ECME, disappearing ECME, giant ECME, possibly quadrupole component ECME in CU Vir (Das and Chandra 2021), none of which is well-understood. Hence it is likely that we have only scratched the surface of this phenomenon in MRPs.

Lastly only Galactic MRPs are known due to their limited optical brightness. However, there may be close by extra-galactic MRPs which may not be observed via traditional methods, but we may be able to see ECME emission from them.

DSA-2000's impact

DSA-2000 is going to carry out a survey of three LSST deep fields: XMM-LSS field, Extended Chandra deep field south and COSMOS fields. These three fields will be observed with daily cadence for 5 years. The sensitivity will be 100 nanoJy/beam and full stokes images will be provided. In addition, the NANOGrav collaboration is currently carrying out regular pulsar timing observations of about 80 pulsars. By the time DSA2000 comes online, they anticipate 200 pulsars suitable for pulsar timing observations. DSA2000 has 25% time reserved for these pulsars, which will be observed at weekly cadence and images of the FOV will be provided to the community.

As DS2000 FOV is 10 sq-deg, there are significant chances that the FOV may contain known or unknown MRPs. A quick search of the three deep fields did not result in a known MRP in the FOV. However, a search of around 35 pulsars observed by NANOGrav collaboration revealed presence of around a dozen magnetic massive stars and two known MRPs. The daily or weekly cadence full stokes images of the deep fields or NANOGrav fields, respectively, means we will be covering known/unknown MRPs in these fields several times at several rotational phases including nulls. This will open up a new parameter space and is likely to result in discovery of unknown Galactic/extragalactic MRPs, long period MRPs, MRPs whose ECME is shifted from nulls and enable characterize the evolution of ECME properties of MRPs as a function of time.

System requirements / desired additions to baseline design (see table below)

To meet our science goals, we require that full stokes images of three LSST deep fields: XMM-LSS field, Extended Chandra deep field south and COSMOS field as well as that of ~ 200 NANOGrav pulsars' FOV be provided to the community.

Table 3.3: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Pointing	all sky	3 LSST deep fields and 200 NANOGrav fields
Cadence	1 every 4 months	daily to weekly for 3 LSST deep fields and NANOGrav pulsar fields
need for additional modes	N/A	full stokes images of the above fields

3.5 Probing Radio Emission from Low-Mass Stars with Circular Polarization Surveys

Authors: Christene Lynch (UNC-Asheville)

Summary

Radio flaring activity occurs in almost half of low-mass stars, the dominant population of stars in the Galaxy (White, Jackson, and Kundu 1989). Yet, the primary mechanism producing radio emission in these stars is currently unknown. Traditionally, attempts to understand radio emission from magnetically active stars have been made within the solar activity paradigm (Bastian 1990). However, low-frequency stellar emissions show properties dissimilar to the solar paradigm. In particular, there are few observations showing a direct correlation of low-frequency radio emissions with optical or X-ray activity in low-mass stars. Also, there are key differences in the observed flare properties (e.g. polarization, dynamic spectrum morphology) for solar and stellar low-frequency bursts. Recently, low-frequency radio observations of two late-type dwarf stars show that these objects can generate magnetic emissions similar to that of magnetic planets via large auroral current systems (Lynch et al. 2017; Zic et al. 2019) or solar-like emissions through electron acceleration possibly associated with coronal mass ejections (Zic et al. 2020). Future radio campaigns to detect and characterize the magnetic emissions of radio bright low-mass stars are required to determine whether solar-like or planetary-like emissions dominate in this population of stars. With recent advances in techniques to identify stellar emissions in large-scale surveys using polarization (e.g., Lenc et al. 2018a; Pritchard et al. 2021; Pritchard et al. 2023), we can now limit the number of false-positive matches in large-scale radio surveys, including those conducted by DSA-2000.

State of the Field

The majority of radio bright stellar objects have been detected using observational campaigns targeting objects with previously known magnetic activity (e.g., White, Jackson, and Kundu 1989; Villadsen and Hallinan 2019a). While targeted surveys can give some insight into the role of stellar parameters on the characteristics of stellar radio emission, they suffer from selection effects that compromise statistical correlations. There are also a few unbiased, volume-limited surveys for stellar radio emissions (e.g., Kimball et al. 2009). Unfortunately, these surveys are limited by the high surface density of background radio sources and resulted in many false-positive matches. However, the radio background is much less saturated in sources that emit highly circularly polarized light. Stellar emissions at low- frequencies ($\lesssim 4$ GHz) are dominated by highly circularly polarized coherent emission processes (Bastian 1990). Few other astronomical sources produce similarly polarized emissions, thus the polarization properties of stellar emissions can be used to uniquely identify stars in large full-polarization radio surveys.

The effectiveness of polarization searches was first demonstrated by Lynch et al. 2017, who detected variable 154 MHz emissions from the low-mass star UV Ceti using stokes V imaging. This work led to the first all-sky circular polarization surveys at MHz (Lenc et al. 2018a) and GHz (Pritchard et al. 2021) frequencies which discovered new radio-bright objects. Recently there have been further surveys at radio frequencies which used polarization searches to identify new radio bright stars (Callingham et al. 2023; Vedantham et al. 2020) and to study time-domain properties, revealing flare repetition rates and properties (Pritchard et al. 2023).

DSA-2000's impact

The DSA-2000's large survey speed and increased sensitivity over current radio survey instruments is ideal for discovering and characterising the radio star population. Using the Rapid Australian Square Kilometre Array Pathfinder (ASKAP) Continuum Survey (RACS), an all-sky survey of the radio sky south of $\delta=+40$, Pritchard et al. 2021 placed constraints on the expected surface density of detectable radio stars at ASKAP sensitivities to be $9.66 \times 10^{-4} \text{deg}^{-2}$. Assuming the population of stellar bursts is Euclidean, we can scale the ASKAP radio star density to DSA-2000 sensitivities. Doing this, we expect both the DSA-2000 all-sky and pulsar surveys to discover between $4\text{--}8 \times 10^4$ stars per observing epoch. The deep stare of the LSST fields is expected to reveal a factor of 10 less stars per epoch ($\sim 10^3$ stars). The DSA-2000 surveys will discover radio stars in numbers that are several orders of magnitude greater than the currently known population of radio stars. With this large population of radio stars we will start to be able to do population statistics and gain a better understanding of what types of stars are expected to produce detectable levels of radio emission.

System requirements / desired additions to baseline design (see table below)

From current all-sky transient surveys using the Australian Square Kilometre Array Pathfinder (ASKAP) we find that surveys with large-sky coverage and many repeats discover more stellar variable emission than observing strategies that involve deep stares on single fields (Pritchard et al. 2021). Further, the majority of the stars that are discovered with ASKAP are new detections and not repeat detections of the same set of stars (Pritchard et al. 2023). The current strategy of the DSA-2000 project already prioritizes a shallow, all-sky survey with 4 epochs planned. Additional epochs of the DSA-2000 all-sky survey will start to place constraints on how often the variability of radio stars is repeated.

A challenge for transient searches using the DSA-2000 survey products will be distinguishing exotic and rare transients from the fog of stellar bursts expected. Methods using polarization characteristics (Pritchard et al. 2021; Lenc et al. 2018a; Callingham et al. 2023), temporal properties (e.g., Wang et al. 2022), multiwavelength data (Kimball et al. 2009), and spectral properties (Cavallaro et al. 2018) will be necessary to identify the more rare transients from radio stars and other polarized sources of interest like pulsars.

Table 3.4: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Cadence	1 every 4 months	As many epochs as possible

3.6 Delayed Radio Flares from Tidal Disruption Events

Authors: Assaf Horesh

Summary

The DSA-2000 superb sensitivity coupled with its all sky survey observing strategy may revolutionize the study of tidal disruption events (TDEs). Our recent discovery of delayed radio flares from TDEs shows the potential of exploring various times scales of months to years after stellar disruption (even in light of initial null-detections). Some of our findings though were made also thanks to performing high cadence (weekly) observations and we recommend that a small fraction of the DSA-2000 observing time will also be dedicated to a high-cadence survey, albeit with a shallower depth.

State of the Field

The observations of tidal disruptions events (TDEs), when a star is tidally disrupted when it passes too close to a supermassive black hole, continue to provide new unsolved puzzles. There are several complication in building a coherent physical picture of TDEs. For example, it appears as though at least some TDEs are capable of generating *relativistic ejecta*; the best such candidates have been discovered by their long-lasting, non-thermal high-energy emission (SwiftJ 1644+57: Bloom et al. 2011, Burrows et al. 2011; SwiftJ 2058+05: Cenko et al. 2011; SwiftJ 1112-82: Brown et al. 2015). In the case of SwiftJ 1644+57, radio observation were key to trace the high-velocity outflow (e.g., Zauderer et al. 2011; Berger et al. 2012, Cendes et al. 2014). Naturally, one may consider an unification scheme: perhaps all TDEs generate relativistic jets and we observe bright non-thermal emission for on-axis geometries and thermal UV/optical events for off-axis angles. Radio non-detections of several optical/UV TDE candidates (van Velzen et al. 2013; Arcavi et al. 2014; van Velzen et al. 2020; Alexander et al. 2020) challenge this picture. Adding to the confusion, is the discovery of early weak radio emission from several optically discovered TDEs (e.g., ASASSN-14li; Alexander et al. 2016), where the radio emission is found to be originating from a sub-relativistic outflow (rather than from a relativistic jet). The origin of the outflow is still unclear, but may be explained by an outflow from an accretion disk or as the unbound stellar debris. All of these recent findings suggest that not only that the nature of TDEs is still ambiguous but that it is also diverse.

We recently discovered that some thermal TDEs exhibit delayed radio flares, several months and years after optical discovery. Our group has now identified this new phenomenon in several cases (Three that are published: ASASSN-15oi; Horesh et al. 2021a; iPTF16fnl; Horesh et al. 2021b; AT2019azh; Sfaradi et al. 2022) and additional events have now been observed by others as well (e.g., Perlmann et al. 2022; Cendes et al. 2022). As Figure 1 shows, in some cases no radio emission has been detected for several months (or longer) until bright radio flares emerged months and years later. In some other cases, while radio emission is detected initially, possibly originating from a sub-relativistic outflow as in ASASSN-14li, a significant excess in radio emission (appearing as a delayed flare) is observed at late-times.

In the case of ASASSN-15oi, we concluded that the standard scenario, in which an outflow is launched briefly after the stellar disruption, is unable to explain the combined temporal and spectral properties of the delayed flare. A possible explanation is that the flare is due to the delayed ejection of an outflow, perhaps following a transition in the super-massive black hole accretion state. Some delayed radio flares, however, may be due to off-axis jet emission (see Matsumoto & Piran 2022). In the case of AT 2018hyz (Cendes et al. 2022, and also Horesh et al. 2022), it was shown recently, that the delayed emissions (observed on a timescale of

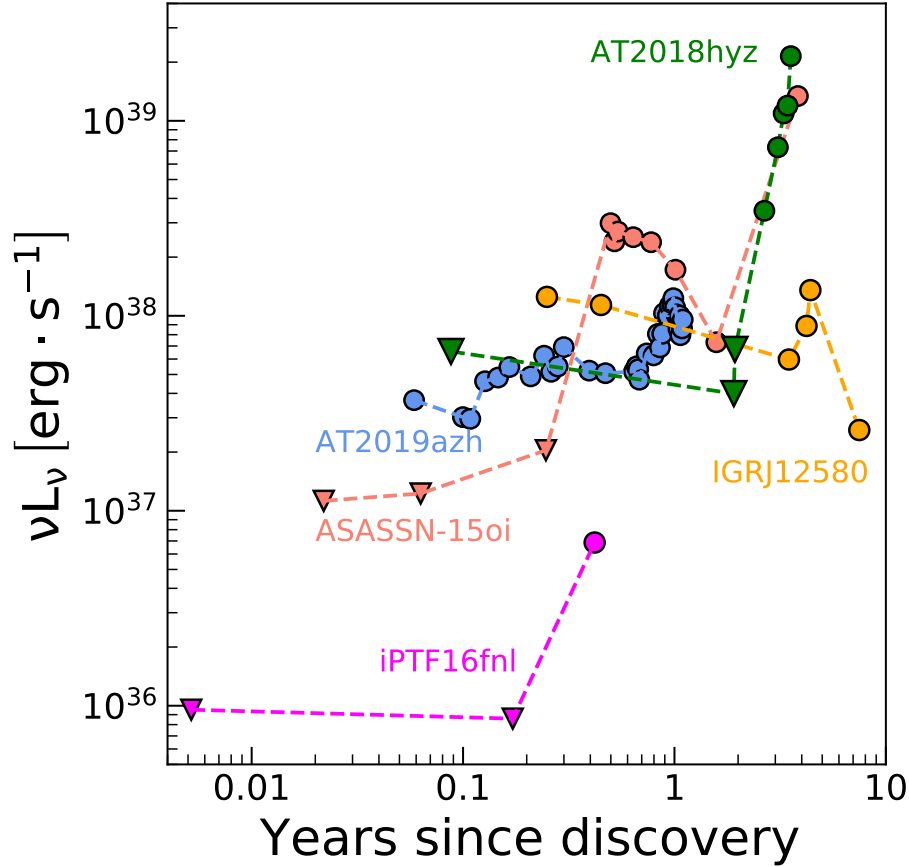


Figure 3.2: The radio luminosities as a function of time of a handful of TDEs exhibiting delayed radio flares (Horesh et al, 2021a; Horesh et al. 2021b, Sfaradi, Horesh et al. 2022, Perlman et al. 2021, Cendes et al. 2022). While late-time radio emission is observed in several past TDEs, the emission in these cases is consistent with a model of an outflow launched briefly after stellar disruption. However, in the cases presented in this plot the radio limits at early time combined with the delayed radio flare observed cannot be accounted for by this model and possibly require the delayed launching of an outflow. In the case of ASSASN-15oi, there are two delayed flares with the second one being brighter and appearing several years after the first one. Analysis of the radio spectra of ASSASN-15oi and its evolution suggests that it is not consistent with standard models (Horesh et al. 2021a).

years) can be explained by such an off-axis jet model (Sfaradi et al. 2023). Recently, Cendes et al. (2023) found that a large fraction (close to 40%) of TDEs exhibit late-time re-brightening in the radio on a time scale of years.

While the case of ASASSN-15oi shows the importance of exploring various time scales, the case of AT2019azh demonstrates the need for high-cadence observations. Our high-cadence weekly observations performed with the AMI radio telescope, revealed that while initially "regular" radio emission emerged from the event briefly after stellar disruption, it was followed by a delayed radio flare (Sfaradi et al. 2022). In contrast, sparse VLA data missed the complicated behavior of the radio emission completely. In this event our observations also showed for the first time that the delayed radio flare followed a delayed X-ray flare. We also note the resemblances to features observed in X-ray binaries, perhaps suggesting common underlying physical processes.

DSA-2000's impact

The DSA-2000 will play a key role in creating a census of radio emission from TDEs, including delayed radio flares. While most standard follow-up radio observations today achieve a sensitivity of $10 - 30 \mu\text{Jy rms}$, the design sensitivity of the DSA-2000 will help increase the detection horizon for radio emission from TDEs by a factor of ~ 5 on average. Moreover, since the DSA-2000 all-sky survey will span several timescales of months to years it will help systematically characterize delayed radio flares that turn on only at these late times.

System requirements / desired additions to baseline design (see table below)

Identifying transient sources at centers of galaxies is difficult, thus having better resolution will be very helpful. I recommend, if possible, to attempt achieving arcsecond (or below) resolution. In addition, one has to be careful with the array design so it will not be too core-heavy. Past experience shows that for point sources, core-heavy arrays were unable to reach the design sensitivity. A further recommendation is to examine the possibility to conduct a shallow high-cadence survey for transients using a small fraction of telescope time.

Table 3.5: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Spatial resolution	3.5"	Preferably $\leq 1''$
Cadence	1 every 4 months	✓ + A high-cadence survey

3.7 Relativistic Stellar Explosions

Authors: Anna Y. Q. Ho (Cornell University)

Summary

Relativistic stellar explosions are systems in which accretion or rotation of a newborn compact object drives a powerful outflow. For decades, the only firmly established example was long-duration gamma-ray bursts (GRBs), thought to represent the case in which black-hole accretion drives a narrow ultra-relativistic jet. However, in recent years the landscape has broadened dramatically, because discovery methods have expanded from solely gamma-ray satellites to include time-domain surveys at other wavelengths. The physical connections between emerging classes-GRBs, “orphan” afterglows, low-luminosity GRBs (LLGRBs), and luminous fast blue optical transients (LFBOTs)-are uncertain, but likely include differences in end-stage stellar evolution, compact-object accretion, and jet properties. By increasing the discovery rate of each of these classes by orders of magnitude, and providing low-frequency radio light curves spanning weeks to years post-explosion, DSA-2000 will help reveal their underlying physical connections.

State of the Field

Off-axis “orphan” afterglows: Decades of off-axis LGRB searches have resulted in several candidates (Cenko et al. 2013; Law et al. 2018; Ho et al. 2020; Mooley et al. 2022; Ho et al. 2022b) but no confirmed discoveries. The low cadence of current surveys, the incomplete coverage of γ -ray satellites, and the lack of multiwavelength data makes it difficult to determine if a given event is truly off-axis. *LLGRBs:* In the nearby universe ($z \lesssim 0.1$), a half-dozen LLGRBs or relativistic Ic-BL SNe have been identified (Bromberg, Nakar, and Piran 2011; Cano et al. 2017). The LGRB-LLGRB connection is unclear due to the small number of well-studied events; suggestions including viewing angle (Izzo et al. 2019), jet “success” (Nakar 2015), and jet power (Irwin and Chevalier 2016). One possibility is that LLGRBs and relativistic SNe represent off-axis LGRB cocoon emission (De Colle, Kumar, and Aguilera-Dena 2018; Izzo et al. 2019). *LFBOTs:* The discovery of the transient AT2018cow (Prentice et al. 2018) and several similar events (Coppejans et al. 2020; Ho et al. 2020; Perley et al. 2021; Yao et al. 2022) established a new class of relativistic explosions dubbed LFBOTs (Metzger 2022). LFBOTs differ from LGRBs in several ways, including hydrogen-rich spectra (e.g., Perley et al. 2019; Margutti et al. 2019), low nickel masses (e.g., Perley et al. 2021), and a central engine duration of months rather than seconds (e.g., Yao et al. 2022). Only AT2018cow itself has a detailed low-frequency radio light curve (Nayana and Chandra 2021), and it is unclear to what extent LFBOT-like radio emission occurs among other types of transients (i.e., to what extent their current optical-based selection is biased).

DSA-2000’s impact

DSA-2000 can increase the discovery rate of relativistic explosions outside the γ -ray band by orders of magnitude, and provide low-frequency radio light curves for years post-explosion. This data will help elucidate the physical connections between the above classes by (1) discovering the first confirmed off-axis LGRBs, measuring the GRB volumetric rate, and studying the cocoon properties of a jet produced by a collapsar; (2) measuring the volumetric rate of LLGRBs and their progenitor radius at the time of explosion; and (3) determining the diversity of LFBOT outflow properties.

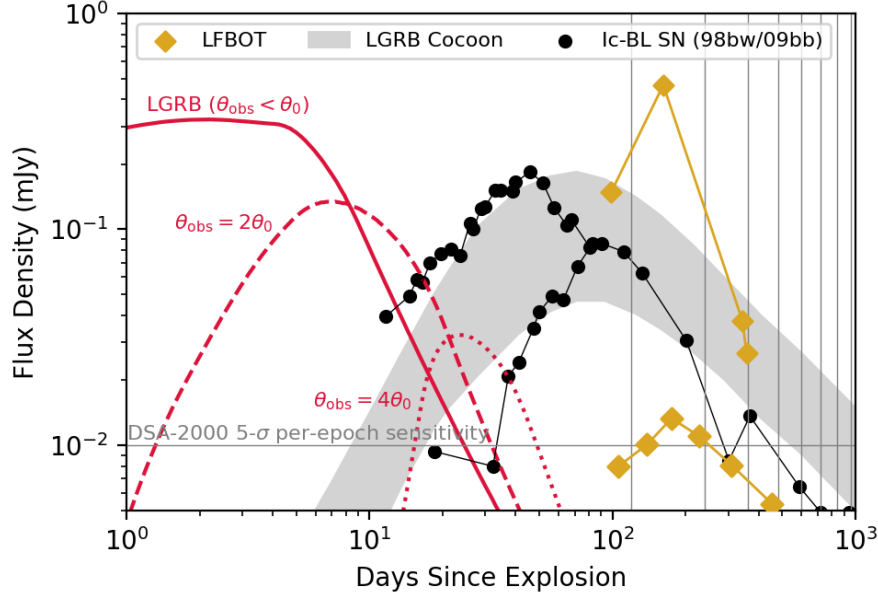


Figure 3.3: Collage of radio (≈ 1 GHz) light curves of relativistic stellar explosions, including observed light curves of the LFBOTs AT2018cow (Margutti et al. 2019) and CSS161010 (Coppejans et al. 2020) and the Ic-BL SNe SN1998bw (Kulkarni et al. 1998) and SN2009bb (Soderberg et al. 2010); and models for LGRB cocoon emission (De Colle, Kumar, and Aguilera-Dena 2018) and LGRB afterglows at three different viewing angles (Ryan et al. 2020). The horizontal line marks the DSA-2000 5- σ sensitivity threshold, and the vertical lines mark observing epochs given the nominal 4-month cadence.

Class	$\mathcal{R}_\nu$ (% CC SN)	$L_{\nu, 1 \text{ GHz}}$ ($\text{erg s}^{-1} \text{ Hz}^{-1}$)	z_{lim}	$\mathcal{R}_{\text{DSA}}$ (yr^{-1})
LGRB cocoon (30° off-axis)	0.01–0.1	5×10^{28}	0.4	10–100
LGRB cocoon (90° off-axis)	0.01–0.1	1×10^{28}	0.2	10–100
LGRB afterglow ($\theta_{\text{obs}} < \theta_0$)	0.01–0.1	5×10^{30}	1.1	7–70
LGRB afterglow ($\theta_{\text{obs}} = 2\theta_0$)	–	2×10^{30}	1.1	30–300
LGRB afterglow ($\theta_{\text{obs}} = 4\theta_0$)	–	5×10^{29}	1.0	90–900
Relativistic Ic-BL SN	0.01–0.1	10^{28}	0.2	10–100
Radio-loud LFBOT	0.01–0.1	$10^{27}–10^{29}$	0.06–0.5	0.6–2000

Table 3.6: Projected rates of DSA-2000 detections for classes of relativistic stellar explosions, assuming a survey with sufficient cadence for all events to be identified. We adopt a local core-collapse supernova (CC SN) rate of $10^5 \text{ yr}^{-1} \text{ Gpc}^{-3}$ (Perley et al. 2020), and for other classes adopt rates from Ho 2020 (Table 1). For LGRBs we assume a jet opening angle of 0.1 radians and correct for beaming. Radio luminosities are adopted from models (De Colle, Kumar, and Aguilera-Dena 2018; Ryan et al. 2020) or observations (Fig. 1). For DSA-2000 we assume a 5- σ limit per epoch of 0.01 mJy (Fig. 1) and a field of view of $30,000 \text{ deg}^2$.

System requirements / desired additions to baseline design

As shown in Figure 1, the current DSA-2000 cadence is well suited for LFBOT observations, but is too slow to resolve the light curves of LGRBs and LLGRBs, on- or off-axis. A faster cadence of 1 week, even over a smaller area of sky (or with less sensitivity), would enable these faster phenomena to be discovered.

3.8 Anomaly detection & unsupervised learning for DSA-2000

Authors: Dovi Poznanski

Summary

In my talk I argued that unsupervised machine learning tools are a necessary addition to our arsenal as we generate larger and larger datasets. These can no longer be examined by experts by eye to identify outliers, either astrophysical or instrumental. The same family of tools can also help us discover new relations in complex multidimensional data, beyond the ones that are already known.

Since these tasks of 'metric learning' or outlier detection are loosely defined, there is no optimal choice nor optimal results, and there is a variety of algorithms that each could potentially uncover a different aspect. With traditional ML algorithms these choices begin with 'feature selection', the crafting of informative input data to the algorithm (e.g., by measuring emission line properties in spectra, or the period of a variable star), and continue with the algorithm used and its hyper-parameters (e.g., the number of trees used in a Random Forest).

Deep algorithms supposedly circumvent that, as they have shown tremendous success at various tasks while being fed the raw 'pixel' data. While this is true, the choice of the architecture of the network, its components, determine the symmetries and properties an algorithm can naturally ignore or learn. For example, convolutional neural networks are excellent at image classification tasks, because they effectively look for patterns anywhere in the image via convolution, and a cat is a cat, no matter where it appears in the image. The opposite is true for language, where the order of words does indeed matter, which (partly and superficially) explains the success of Transformer based architectures (the T in the now infamous ChatGPT) that learn and maintain the order of words.

I discussed efforts by my group and others in the community to first apply what we think would be the most informative algorithm to various datasets, analyze the results ourselves, but then also create interactive visualizations of the learned products, in order to allow astronomers in the relevant sub-field access to these views.

In the specific context of DSA-2000 one will need to define the most interesting 'spaces' where to apply these techniques. At what level of the data analysis and interpretation. For example, ML can be applied on light curves from the deep fields, or on cross-matched sources between DSA and other surveys.

3.9 Type Ia Supernova Progenitors through Circumstellar Environments

Authors: Chelsea E. Harris

Summary

Some Type Ia supernovae (SNe Ia) show evidence of circumstellar material (CSM), primarily in the form of an optical interaction shock which should have a radio counterpart. However, the CSM around SNe Ia seen so far has been essentially anything but the low-density wind that was expected from progenitor theory. The intrinsic rarity of SNe Ia with CSM, combined with the unknown density and location of the CSM (which may be intrinsically random) makes it difficult to design targeted radio campaigns to detect these shocks. Instead, an all-sky survey like DSA-2000 is the best strategy for successfully detecting radio emission from SNe Ia, though this science program benefits significantly from having a real-time alert stream that utilizes optical surveys like LSST.

State of the Field

Radio observations of Type Ia supernovae (SNe Ia) are used to study their circumstellar media (CSM) – via synchrotron radiation emitted from the blast wave formed by ejecta-CSM interaction – in order to determine their stellar progenitors. In the symbiotic “single-degenerate” scenario, SNe Ia are the explosions of carbon-oxygen white dwarfs that have accreted mass from the wind of a red giant (RG) companion, approached the Chandrasekhar limit, and ignited runaway thermonuclear burning (Iben and Tutukov 1984). Since this is a relatively dense wind – compared to other single-degenerate companions, like main sequence stars – historically, the focus of radio observations has been to distinguish whether SNe Ia are surrounded by **RG winds**. Radio emission from the interaction of an SN Ia with an RG wind has never been observed, from which Chomiuk et al. 2016 limit symbiotic RG companions to $\lesssim 10\%$ of SNe Ia.

However, at optical wavelengths, the presence of CSM has been indicated by a variety of observations for at least some SNe Ia, but the CSM properties are diverse. **(1) SN IIn-like:** SNe with significant optical shock emission at all times and an underlying SN Ia (specifically, 91T/99aa-like) spectrum, indicating interaction with an extremely dense, wind-like CSM. **(2) Early Excess:** SNe Ia with excess optical emission in the first $\sim$ days post-explosion, indicating interaction with a compact CSM. **(3) Delayed Interaction:** SNe Ia with excess optical emission appearing $\sim$ months post-explosion, indicating interaction with a detached CSM. **(4) Narrow Absorption:** SNe Ia with time-variable or blueshifted narrow absorption features from distant CSM (ejecta-CSM interaction not seen). However, predicting the radio signal to design a targeted search is difficult: the radio light curve reflects the shock evolution, the shock evolution reflects the CSM density profile, and the CSM density profile is not known *a priori*. The existence of various optical interaction groups indicates that we should be prepared for a range of radio light curve properties. We are therefore at a point where we have moved far beyond the confines of RG winds and into an exciting realm of ignorance that is ripe for discovery.

Fortunately, all SN Ia CSM groups besides the Early Excess can have late-time interaction that should evolve slowly (due to a long hydrodynamical timescale) and increase the detection window. Indeed, an SN Ia, SN 2020eyj, has now been detected at radio wavelengths with a 5.1 GHz luminosity of $L \sim 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$ at ~ 600 and ~ 740 days post-explosion (Kool et al. 2023). SN 2020eyj belongs to the Delayed Interaction CSM group, and is the first example of an SN Ia with helium-rich, hydrogen-poor CSM. It is worth noting that radio observations are typically not requested at such late phases, because wind models of interaction peak much earlier. This demonstrates how the non-detection-riddled, wind-focused history of SN Ia radio observations

may be introducing bias into this field when we are dependent on triggered observations for deep limits.

DSA-2000's impact

SNe Ia show much more complex behavior in their CSM than anticipated from progenitor models. An all-sky radio survey is powerful for SNe Ia because, with a slew of non-detections in the history of the field, it is difficult to justify deep, large-sample, multiple-epoch, disruptive observing campaigns – however, this is exactly where the discovery potential is for SNe Ia. DSA-2000 will achieve competitive limits with $2 \mu\text{Jy}$ observations, reaching $L_\nu \sim 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$ out to $d_L \sim 200 \text{ Mpc}$. DSA-2000 will sample the environment at multiple radii “for free” (at 120-day intervals) and probe out to $r \sim 10^{17} \text{ cm}$ for many events due to its 5-year lifespan, which is critical because we do not know the location or extent of SN Ia CSM a priori. When we consider using DSA-2000 and LSST together, the potential is easily illustrated. The LSST Main survey will observe $\sim 1.25 \times 10^5$ SNe Ia per year (with a signal-to-noise ratio at maximum light of > 15 and two filters), and ~ 800 will be within 200 Mpc, per the expected redshift distribution (LSST Science Collaboration et al. 2009). Then, in five years of DSA-2000 CASS, even if only half the sky area overlaps between the two surveys, we will still have observations down to $L_\nu \sim 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$ for $\sim 2,000$ SNe Ia – the current sample size is ~ 70 ! The currently planned cadence of DSA-2000 is roughly one per 120 days, and expected interaction signals can be visible for a much shorter time than this; however, the sheer number of SNe Ia in DSA-2000+LSST still makes it a competitive survey. For example, DSA-2000+LSST may observe ~ 600 SNe Ia down to $L_\nu \sim 10^{25} \text{ erg s}^{-1} \text{ Hz}^{-1}$, which can detect a $10^{-8} M_\odot \text{ yr}^{-1} / (10 \text{ km s}^{-1})$ wind (low density RG wind) for ~ 40 days. There is only a 1/3 chance of each SN being observed at the right time, but is still ~ 200 events compared to the current sample size of about one dozen (Harris et al. 2023)!

System requirements / desired additions to baseline design (see table below)

To optimize the potential of DSA-2000 for SN Ia science, its data stream needs to be connected to public optical surveys (like LSST) so that detected radio transients can be matched to SNe in real time. If this is done, it will enable timely follow-up with other radio instruments to (a) characterize the shape of the radio SED, (b) follow the radio evolution with higher-cadence observations, and (c) obtain the spatial resolution needed to confirm an association with the SN Ia. If DSA-2000 data are not monitored in conjunction with optical surveys in real time, then their power will be primarily statistical. Spatial resolution will likely be an issue with using the DSA-2000 dataset to study SNe Ia, especially out to $\sim 200 \text{ Mpc}$.

Table 3.7: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Spatial resolution	3.5"	need higher res

3.10 Supernovae

Authors: Michael F. Bietenholz

State of the Field

Core collapse supernova (SNe; Types Ib, Ic and II) represent the endpoint of almost all massive stars. They are responsible for both, chemical enhancement of, and the injection of a substantial amount of energy into, the ISM. The synchrotron emission from SNe can uniquely probe the SN explosion mechanism, the SN's environment, and the properties of the black holes (BH) and neutron stars (NS) born in the explosions. The SN shock interacts with the mass lost by the star before it exploded, and the radio emission gives a very valuable probe into the important, but poorly-understood, mass-loss from massive stars. Radio emission from SNe allows us to address many questions, including (i) What are the properties of the eruptive mass-loss episodes in the years prior to explosion that are not predicted or explained by our current understanding of massive star evolution? (ii) What progenitor star properties lead to central engines powerful enough to drive relativistic outflows? (iii) What are the properties of these young (years to decades old) NSs and BHs?

So far, radio observations have almost exclusively been obtained from SNe that were first detected optically. However, optical observations do not catch all SNe: two notable examples which were first detected in the radio rather than optically are SN 2008iz at 3.8 Mpc (e.g., Brunthaler et al. 2010) and SN 1986J at 10 Mpc (e.g., Bietenholz and Bartel 2017a). Even in our own Galaxy, the likely most recent SN, about 100 yr ago, was not optically detected, but the resulting remnant has been identified in radio (Murphy, Gaensler, and Chatterjee 2008). The radio observations of SNe are very incomplete beyond ~ 20 Mpc.

Clearly, for a complete census of SNe, especially in dusty environments near the centers of galaxies, radio observations are necessary. DSA-2000, with its complete sky coverage and high sensitivity, will be an ideal vehicle to detect radio supernovae in an unbiased fashion.

Furthermore, most SNe are only observed in the radio for a relatively short period after the explosion, and often with poor temporal coverage. There have a few cases of SNe observed to re-brighten in radio at late time, but in most cases, such late-time emission would not be seen. Some examples of this were caught by chance in the Very Large Array Sky Survey (VLASS; Stroh et al. 2021b). DSA-2000, unlike VLASS, would provide regularly sampled lightcurves for such events, allowing a complete history of their behaviour to be determined, as well as providing much more complete temporal coverage for detecting them in the first place. Both the resolution and sensitivity of DSA-2000 will be superior to those obtainable with MeerKAT (e.g., Fender et al. 2016) and ASKAP (e.g., Murphy et al. 2021), making it DSA-2000 better suited for radio observations of SNe.

By examining the majority of the existing radio observations of SNe, including many non-detections, Bietenholz et al. 2021 showed that the median of the peak radio spectral luminosity, $L_{\nu, \text{pk}}$, of SNe was¹ $\sim 10^{25.5} \text{ erg s}^{-1} \text{ Hz}^{-1}$. The $2 \mu\text{Jy}$ sensitivity of DSA-2000 will allow a 5σ detection of this median $L_{\nu, \text{pk}}$ out to ~ 50 Mpc, and DSA-2000's $\sim 3.5''$ resolution will be sufficient in most cases to isolate the supernova from its host galaxy. Importantly, DSA-2000 would be able to detect also many SNe from the half of the population below this median $L_{\nu, \text{pk}}$, about which little is known, although we do have the prominent example of SN 1987A with $L_{\nu, \text{pk}}$ at early times of 1% of the median value (it decayed initially, but rose to above these values after the age of 25 yr).

DSA-2000 will therefore provide an unprecedented census on the radio emission of SNe, much more complete, unbiased, and regularly sampled than the ad-hoc observations that are currently available, and will

¹This value obtains at $\nu = 5 - 10$ GHz the $L_{\nu, \text{pk}}$ in the DSA-2000 band would be of similar order, but perhaps slightly higher

almost certainly find new and interesting types of radio SNe, and provide a much better understanding of the radio emission of the whole population of SNe.

3.11 Long-period radio transients

Authors: Natasha Hurley-Walker (International Centre for Radio Astronomy Research, Curtin University)

Summary

A new class of periodic radio transients currently challenges our understanding of radio emission from compact stellar remnants. As they repeat on ~ 20 -minute timescales, the short integration times of most wide-area sky surveys have so far yielded only a handful of examples. Their emission is not well-explained by known physical theories. The DSA-2000 will have the sensitivity and imaging quality to detect orders of magnitude more of these sources than current surveys, enabling a true understanding of their physical nature, and how they connect to stellar evolution and death, and whether they are progenitors of Fast Radio Bursts.

State of the Field

Recent radio-frequency surveys have uncovered a population of long-period radio transients (Hurley-Walker et al. 2022; Hurley-Walker et al. 2023). These produce pulsed emission with durations of seconds to minutes, which is usually highly linearly polarised, indicating the presence of ordered magnetic fields. These pulses are periodic on timescales of minutes to hours, and can exist within short activity windows or persist for decades. The mechanism to generate the emission is unclear, but the transients are generally interpreted to be rotating magnetic compact objects, producing a beam of continuous emission, which crosses the line-of-sight of the observer with a periodicity equal to the rotation rate, similar to pulsars.

Unlike pulsars, they cannot be spin-down powered, as they have radio luminosities greater than their spin-down luminosities, and lie below the pulsar “death lines” (Fig 3.4). While ultra-long period magnetars (ULPMs) are a potential explanation (e.g. for a source with $P = 76$ s discovered by Caleb et al. 2022), it is unclear how some sources can have persistent radio emission for decades, implying a constant source of magnetic energy, which should disrupt the neutron star crust – yet also generate no detectable X-ray emission. If they are ULPMs, they could be candidate progenitors for Fast Radio Bursts (Beniamini, Wadiasingh, and Metzger 2020; Beniamini et al. 2023). Other explanations include Ar Sco-type systems (although such systems have $\sim 1000\times$ lower radio luminosities and different polarisation properties; see Pelisoli et al. 2023), isolated white dwarf pulsars (Katz 2022), and even exotic objects like quark stars. As yet there is no consistent physical explanation for the discovered sources, making them an exciting class that could yield novel astrophysics.

DSA-2000’s impact

With only a handful of known objects, each of which has different activity windows, periodicity, pulse width, and duty cycle, it is difficult to draw conclusions about whether these are a single diverse class, or two or more new types of object. Finding more examples will enable multi-wavelength follow-up toward nearby objects that could be expected to have detectable optical and/or X-ray counterparts, a more complete view of their radio polarisation behaviour that would illuminate their emission mechanism, as well as population-level analyses that examine their distribution throughout the Galaxy, range of periodicities, duty cycles etc. All of these would help determine their true physical nature. The sensitivity of DSA-2000 may enable, for the first time, detection of these sources outside the Milky Way. The DSA-2000 will observe over a frequency range germane to the detection of these objects, which have largely been discovered and followed up at 200 MHz–1.4 GHz, above which their spectra become steep

and making them difficult to detect; this frequency range also yields relatively low scattering, increasing the volume into the Galaxy over which they may be detected. Large sky coverage is necessary to detect many examples in an unbiased way. A declination limit of $> -31^\circ$ includes the Galactic centre and over 50% of the expected population, if they have a similar distribution throughout our Galaxy to pulsars. 3.5'' resolution will yield sub-arcsecond position precision for reasonable S/N sources, more than sufficient for optical cross-matching (e.g. with Gaia). Polarization is essential for understanding the emission mechanism and at 2 MHz, the DSA-2000 will be able to successfully measure linear polarisation for sources with rotation measures expected for the Galactic population $\lesssim 7,500 \text{ rad m}^{-2}$. A cadence of one sky every four months is very well suited to some sources that are seen to be active over a few months (Hurley-Walker et al. 2022, Caleb et al. in prep).

Field-of-view is the ultimate enabler for detecting extremely rare sources, and this is where the DSA-2000 will be the ideal transient-hunting machine. If, as with many other astrophysical objects, there is a power-law distribution to the luminosities of the sources, with many more faint than bright, DSA-2000's exquisite sensitivity will enable the detection of at least two orders of magnitude more sources than current surveys such as VAST.

The repeated all-sky survey using wideband continuum imaging can be processed effectively for these transients – first by subtracting a continuum sky model, and then forming dirty images at a time resolution appropriate for the available computing – ideally $\mathcal{O}(1\text{s})$. Various filters may be employed, e.g. a fast and simple search for high-significance peaks, matched filtering, or machine learning. The excellent (u, v) -coverage of the DSA-2000 will ensure highly Gaussian noise and a minimum of false positives. The effective integration time per epoch of 15 minutes is also well-suited to capturing sources with these ~ 20 -minute periodicities, and repeated epochs will increase the chances of detecting sources with higher periods still. This data will likely yield many other interesting transient and variable sources.

System requirements / desired additions to baseline design (see table below)

No additional system requirements are needed. Computationally, dirty images of each 10–15-minute observation will need to be formed on 1–10 s cadences and rapidly searched for transients. This is computationally feasible already with such systems running on ASKAP (Wang et al. 2023), LOFAR (de Ruiter et al. in preparation), and the MWA (Hurley-Walker et al. in preparation).

Table 3.8: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Desired mode:	Imaging on 1-s timescales	

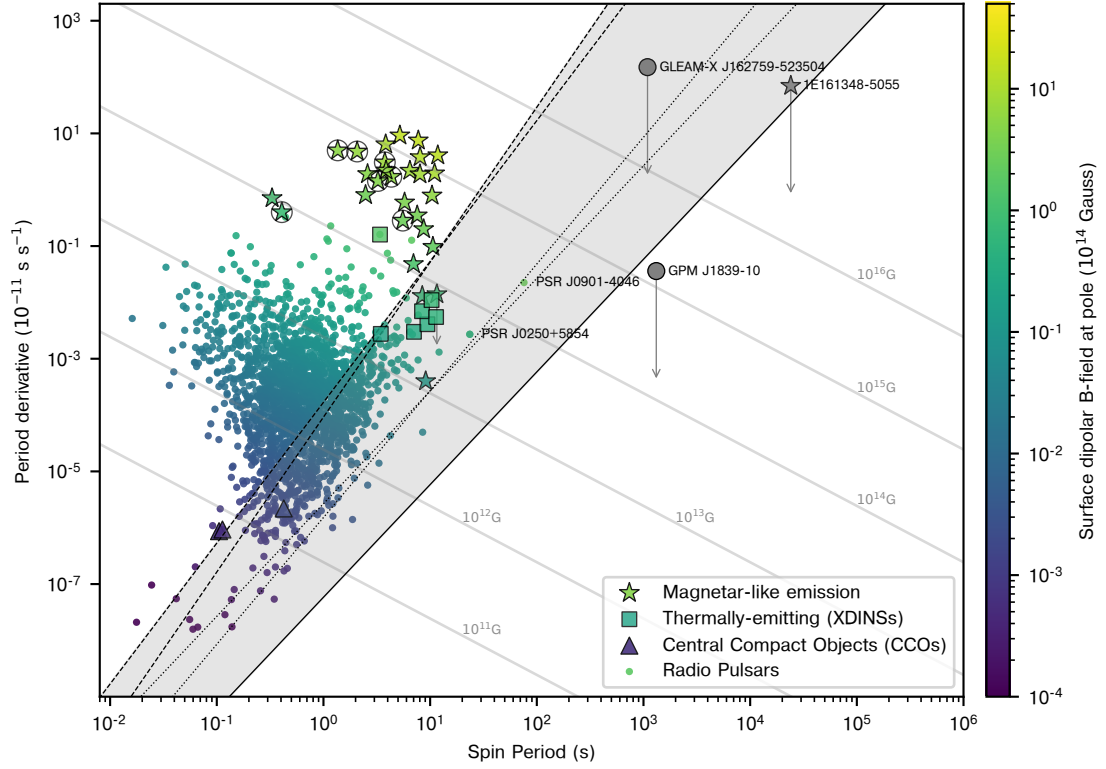


Figure 3.4: The period – period derivative diagram for the known pulsars and the new long-period radio transients. GPM J1839–10 lies beyond the most extreme “death lines” of spin-down powered radio emission in radio pulsars, implying a different emission mechanism that has yet to be revealed. Figure reproduced from Hurley-Walker et al. 2023.