

Chapter 4 The Dynamic Radio Sky: Fast Transients

Summary: Fast Transients

Authors: Shami Chatterjee and Bing Zhang (on behalf of the SAC)

The time domain has been a frontier for discovery in astronomy, as exemplified by “fast” radio transients, which are loosely defined as the subset of transient phenomena where pulse dispersion by the interstellar (and intergalactic) plasma is relevant. The discovery of pulsars in 1967 kicked off a gold rush as radio surveys identified more extreme examples and enabled their use as astrophysical laboratories for a broad range of applications, from probing the equation of state for ultra-dense matter, to mapping the Galactic distribution of the interstellar plasma, and much more. Intermittent pulsars, rotating radio transients (RRATs), and transient radio pulsations from magnetars all served to emphasize the expansiveness of the discovery frontier.

Fast Radio Bursts (FRBs) have been one of the most exciting finds on this frontier in the last two decades. These millisecond-duration radio flashes showed pulse dispersion measures ($DM \equiv \int_0^L n_e(l) dl$, where n_e is the electron density along the line of sight) consistent with their origin in distant galaxies, implying very high intrinsic luminosities, while the event rates, inferred from the handful found in archival radio survey observations, were truly prodigious ($\sim 10,000$ events/day all over the sky beamed towards us, depending on telescope sensitivity and band; up to $\sim 10^7$ Gpc $^{-3}$ yr $^{-1}$ for the physical rate density). Narrow beaming angles could be invoked to reduce the total energy budget, but at the cost of multiplying the event rate by large factors. The identification of repeating sources, the localization of sources to specific host galaxies at measured redshifts, a large expansion of the sample especially with CHIME and ASKAP surveys, and the identification of a Galactic analog, have all served to tame the torrent of theoretical models. Magnetars are now widely considered the most plausible sources for these bursts.

The scientific interest in FRBs broadly relates to (i) the physics of their engines, and (ii) their utility as probes of their propagation paths. The luminosities and short durations of FRBs require their origin in extremely coherent processes. Magnetars are currently the leading candidate for their engines, although FRBs might originate in their magnetospheres (“near” models) or from their interactions with their surrounding nebulae (“far” models). However, many other mechanisms (some of them invoking novel physics, and some suggesting multi-messenger connections) also remain viable. Meanwhile, the propagation, pulse dispersion, and scattering of these FRBs offers a unique probe of the environment in the host galaxy, intervening galaxy clusters, and the intergalactic and circumgalactic media. Early analyses already show consistency with the expected baryon density of the universe, and tomographic maps of the intergalactic medium (IGM) and galaxy clusters will open up a wide range of cosmological applications. A large sample of well-localized FRBs with redshift measurements will probe large scale structure, the reionization history of the local universe, magnetic fields in the IGM, dark matter, and the Hubble constant and other cosmological parameters, as well as constraining fundamental physics such as the speed of the photon and the weak equivalence principle.

In order to realize the full scientific potential of FRBs (and fast transients in general), we require both a large sample of sources, and their distances, from localization to host galaxies. These pose two very different sets of requirements: finding a large sample requires a large field of view and maximizing time on sky, while accurate localization (at $\sim$ sub-arcsecond precision for reliable host identifications) requires high angular resolution during the few-milliseconds burst duration. Combining both of these poses a massive computational and data-management challenge, further exacerbated by the need to search over many trial values of DM. With interferometric imaging arrays like the DSA-2000, two complementary approaches can be explored: imaging the sky at high spatial resolution and on short timescales using visibilities de-dispersed over a range of trial DM values; or creating synthesized beams to tile the field of view and searching each beam over a time-DM grid.

There are rich scientific rewards for tackling this massive computational challenge, as demonstrated by the explosive growth of interest in FRBs and their scientific applications. Meanwhile, the recent discoveries of ultra-long period (minute-scale) magnetars and of sub-microsecond “ultra” fast radio bursts suggest that there is a lot more to find in the fast radio transient sky. The future is bright!

4.1 FRB searches with DSA-2000

Authors: Liam Connor, Vikram Ravi, Casey Law, Myles Sherman

Summary

The DSA-2000 can detect and localize as many as 10,000 fast radio bursts (FRBs) per year, nearly doubling the present sample in its first two days on sky. Searching the full 2000-antenna array in real time will bear significant computational costs and host-galaxy follow-up will require exploiting upcoming optical/IR surveys such as DESI, Euclid, SPHEREx and Rubin/LSST. Such a large sample of localized FRBs with a deep redshift distribution will allow us finally to realize the goal of FRB cosmology.

State of the Field

The engines powering FRBs at extragalactic distances, and the means by which the bursts are emitted, remain little understood. FRB dispersion measures (DMs) and other propagation effects such as Faraday rotation promise are exquisite probes of the total contents and physical conditions of baryons around and in between galaxies, which are otherwise difficult to observe in their entirety.

CHIME/FRB currently leads the world in total FRB detection rate, but without sufficient localization precision to identify host galaxies (CHIME/FRB Collaboration et al. 2021). In its five years on sky, this has produced more than 4000 bursts, most of which are once-off detections with ~ 10 arcmin precision. The most significant scientific impact of that sample was in identifying outliers that could be studied in more detail. For example, the large detection rate has enabled the identification of a $\mathcal{O}(100)$ repeating sources.¹ A few of these have been localized by other interferometers to individual host galaxies, and sometimes regions within hosts, revealing a diversity of host environments from dense star-forming regions (Chatterjee et al. 2017) to globular clusters (Kirsten et al. 2022). Detailed studies of the radio bursts from repeating sources have found highly interesting and suggestive patterns, including quasi-periodicities of burst rate (Chime/Frb Collaboration et al. 2020a), and order unity variations in rotation measure (RM; Anna-Thomas et al. 2023). Between 2018 and 2022, the Australian SKA Pathfinder Telescope (ASKAP) was the premiere FRB localization engine (Gordon et al. 2023), identifying between 5–10 events per year. Major results from the ~ 20 published ASKAP localizations include the first insights into the FRB host-galaxy population, and an empirically derived relation between redshift and dispersion measure (Macquart et al. 2020).

In the past 18 months, the DSA-110 has taken its place as the world leader in FRB localization and host-galaxy identification. It has now tripled the sample of FRBs with arcsecond localization precision during commissioning with 48 core antennas and 15 outrigger antennas at OVRO. Soon it will complete its deployment of the remaining core antennas, leading to a boost in sensitivity and $\sim 2\times$ -higher detection rate. Major new results include the stringent constraints on the baryon content of the Milky Way halo (Ravi et al. 2023), the first FRBs in galaxy clusters (Connor et al. 2023), a surprising population of FRBs in massive hosts (Law et al. 2023), and a census of the polarization properties of FRBs, including the association of RM with the host-galaxy interstellar medium (Sherman et al. 2023b; Sherman et al. 2023a).

DSA-2000's impact

To understand DSA-2000's impact on FRBs, we need to forecast its detection rate and the redshift distribution of those detections. Starting with a simple extrapolation, we can scale the rate from the

¹<https://www.chime-frb.ca/repeaters>

DSA-110 to that of DSA-2000. During commissioning with 48 core antennas, DSA-110 detected roughly one FRB per week. Assuming Euclidean source counts ($N(> F_{\min}) \propto F_{\min}^{3/2}$) and ignoring the larger bandwidth of DSA-2000 for now, this gives a detection rate of ~ 280 FRBs per week or 15,000 per year. A more sophisticated approach can be found in Connor & Ravi (2023), which accounts for the wide-bandwidth and sub-Euclidean source counts at 10 mJy ms level bursts. Using this method and assuming we can use the full array, that also gives $\mathcal{O}(10^4)$ per year. It was also found that the improved sensitivity of DSA-2000 leads to a significantly deeper redshift distribution of sources. The DSA-2000 will be the premiere instrument for the use of FRBs as probes of cosmic baryon evolution.

Within the Astro2020 priority science area “Unveiling the Hidden Drivers of Galaxy Growth”, large samples of DMs towards localized FRBs were noted as a “powerful new probe” of baryon contents around and in between galaxies (see also Ravi et al. 2019). FRB data inform poorly constrained models of galactic feedback, and can break an important degeneracy in using kinetic Sunyaev-Zeldovich measurements as a cosmological probe. Together with observations of large-scale structure from DESI, SPHEREx, Euclid, and Rubin, the DSA-2000 FRB sample will trace the spatial distribution of ionized cosmic baryons, and the ionization history of the intergalactic medium including the process of helium reionization. The DSA-2000 sensitivity enables the discovery of $\gtrsim 10$ strongly lensed FRBs, where accurate time-delays and mass modeling using wave-optics effects are of great promise in Hubble constant measurements.

System requirements / desired additions to baseline design

As a baseline, 10^4 localized FRBs are required to realize the science goals above, including, e.g., a detection of FRB-DESI cross-correlation (Madhavacheril et al. 2019), the detection of $\gtrsim 10$ strongly lensed events (Connor and Ravi 2023a), and tomography of the baryon distribution (Ravi et al. 2019 and references therein). Science goals related to FRB sources and emission are considered secondary in specifying the required number of detections, but are important in defining the data products associated with each FRB. The formal baseline science requirement for the fast time-domain system of the DSA-2000 is for a fast-transient search on 1–1000 ms timescales between DMs of $0\text{--}10^4 \text{ pc cm}^{-3}$, with sensitivity over the full primary beam equivalent to the full observing band. It is additionally required that full-polarization, full-band, post-PFB voltage data be available for each detected FRB, specifically for gravitational lensing, emission-mechanism, and propagation-effect (scattering, Faraday rotation) science.

In practice, several optimizations will be made to achieve (and surpass) the required FRB detection rate. For example, for a fixed number of beams uniformly sampling the sky, excluding data above a certain cutoff frequency does not significantly affect the detection rate. We anticipate forming approximately 10^7 beams and processing approximately 20 gigasamples per second per GPU of intensity data for the fast-transient search.

4.2 Fast radio bursts

Author: Kiyoshi Masui

Summary

DSA-2000 will be one of the world's premier FRB detectors in the late 20's but the technical challenges of the search, especially the computational cost, are significant.

State of the Field

Fast radio bursts (FRBs) are millisecond-duration broadband flashes of radio light coming from cosmological distances. The short timescale implies a compact-object origin, although the precise identities of the progenitors and emission mechanism remains unknown.

The Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst (CHIME/FRB) Instrument is the worlds premier FRB detector, with a detection rate of a few per day. This capability has provided key clues as to the nature of FRBs, including the joint CHIME/FRB–STARE2 detection of an FRB from a galactic magnetar. VLBI followup of repeating FRBs has localized them to a diversity of environments, including sources just outside star forming regions, and to a globular cluster in the halo of M81.

The CHIME/FRB is currently being augmented with VLBI Outriggers—three smaller copies of the CHIME telescope that will be distributed accross North America. These Outriggers will work in tandem with CHIME to localize most CHIME-detected FRBs to 50 milliarcsecond precision.

Beyond their interest as a high-energy astrophysical phenomena, FRBs are promising cosmological probe. The observed dispersion of FRBs provides a precise measurement of the column density of free electrons along the line of sight, which in turn traces the diffuse baryon distribution of the intergalactic medium (IGM). The distribution of the baryons on megaparsec scales is high uncertain since it is hypersensitive to feedback processes in galaxy evolution. By cross-correlating the dispersion of background FRBs with the number density of foreground galaxies, it is possible to measure the free-electron–galaxy cross-power spectrum, which will be a key input for understanding and calibrating feedback models.

DSA-2000's impact

DSA-2000, along with CHORD (the Canadian Hydrogen Observatory and Radio-transient Detector) will be the next-generation FRB detectors after CHIME. Of these, DSA-2000 will have more collecting area and thus be sensitive to fainter, statistically more distant bursts, while CHORD will have better localization precision with its VLBI Outriggers. FRB detections with these instruments could approach 10^5 sources, providing an exquisite dataset for cosmological applications.

System requirements / desired additions to baseline design

[Vikram TBD] The naive computational cost of the DSA-2000 FRB search is extreme. FRB searches are usually dominated by the cost to dedisperse the data. Brute force dedispersers that are used in most searches have a cost scaling as $\mathcal{O}(N_t N_f N_{DM})$, however the newer "tree" algorithms (which are employed by CHIME) scale as $\mathcal{O}(N_t N_f \log(N_f))$. Ignoring the logarithmic factor, the search cost is thus roughly proportional to the input data size.

Critically the factors N_t , N_f , and N_{DM} are not independent. For a given time resolution and target search DM (i.e. the maximum DM for which your search is optimized) the frequency resolution is set

by the requirement that the intra-channel dispersion does not wash out the signal and dilute the time resolution. One consequence of this is that the cost to search at higher time resolutions scales as $(\Delta t)^{-2}$. Another consequence is that, because the dispersion delay is proportional to f^{-2} the optimal frequency resolution is frequency dependent and proportional to $\Delta f \sim f^{-3}$. Lower frequencies are much more expensive to search than higher ones. Alternately, frequency dependent time resolution can be similarly optimal.

The central challenge for DSA is the large number of required search beams due the non-compact array configuration, compounded by the large fractional bandwidth. To fully tile the DSA-2000 FOV at the bottom of the band, using a pixel spacing set by the resolution at the top of the band requires 50 million pixels. With 1 ms time resolution and 10k spectral channels, the total data rate is 5e14 samples/second. Codes currently in use can dedisperse 1e9 samples/s per GPU (2110.03482). A code under development at the Perimeter Institute by Kendrick Smith and Eric Schnetter for use with CHORD can dedisperse 1e10 samples/s/GPU. However, even with such a code, the DSA search remains unfeasible by approximately an order of magnitude.

One route making the search feasible is smart placement of the search pixels. The pixel spacing is set by the resolution at 2 GHz, where the field of view is only 1/9 that at 700 MHz. Thus, with location-dependent spatial resolution there is opportunity for a speedup of a factor of a few. Further savings are possible if you are willing to bisect the search band into two sub bands, with a small sacrifice in S/N for FRBs that span the full observing band.

Independent of the search, having a good calibration of the selection effects of the ultimate system is critical for both FRB population studies and cosmological applications. In such complicated systems and in the presence of RFI, the most accurate and feasible method for calibrating these effects is a synthetic signal injection system (2206.14079). A continuously operating system that injects at least 10^4 (preferably many more) synthetic FRBs into the realtime pipeline daily should be a key requirement for DSA-2000's FRB search.

4.3 Characterizing Host Galaxies of Fast Radio Bursts

Authors: Kritti Sharma, on behalf of the DSA-2000 Team

Summary

The stellar population in the neighborhood of extragalactic transients and their delay-time distributions provide critical insight into their progenitor physics. Historically, such statistical endeavors have played a crucial role in unveiling the nature of progenitors of several transients, such as gamma-ray bursts and supernovae. The venture of characterizing host galaxies of Fast Radio Bursts (FRBs) is essential to disentangle the proposed spectrum of formation channels, ranging from young magnetars formed during core-collapse supernovae to binary neutron star mergers in early-type galaxies. The major challenge in achieving this goal is to obtain their sub-arcsecond localizations. The Deep Synoptic Array-2000 (DSA-2000) aims to bridge this gap by enabling precision localizations with sustained, high-speed monitoring at an FRB discovery rate of 2,000/year.

State of the Field

The studies of fast radio burst (FRB) host galaxies, enabled by arcsecond-scale localization by modern radio interferometers, have attempted to solve the longstanding mystery of these energetic, short-duration enigmatic explosions (Gordon et al. 2023; Bhandari et al. 2022a; Mannings et al. 2021; Heintz et al. 2020). The major conclusions from such studies have been actively incorporated into proposed progenitor models (Petroff et al. 2022, 2019). For example, the association of FRB 20121102 with a dwarf, rapidly star-forming galaxy, and a persistent radio source suggested a young magnetar progenitor (Tendulkar et al. 2017; Chatterjee et al. 2017; Kulkarni et al. 2015). However, the discovery of a repeating FRB 20200120E associated with a globular cluster of M81 indicated that the progenitor was formed in a compact binary coalescence event (Kirsten et al. 2022; Bhardwaj et al. 2021). The diagnostics, such as inferred local environments, galaxy types, and accurately derived physical properties of a large sample of host associations, can help disentangle the proposed progenitor theories and differentiate FRBs from other extragalactic transients (Petroff et al., 2022). These studies can determine if FRBs may be formed via one or multiple progenitor channels since FRBs have been found in a spectrum of environments, including dwarf galaxies (Bassa et al. 2017; Bhandari et al. 2022b), spiral galaxies (Mannings et al. 2021; Fong et al. 2021; Tendulkar et al. 2021; Marcote et al. 2020), elliptical galaxy (Sharma et al. 2023), globular cluster (Kirsten et al. 2022; Bhardwaj et al. 2021) and galaxy clusters (Connor et al. 2023, Sharma et al. 2023). The existing sample of host galaxies of FRBs suggests that they are generally starforming (Gordon et al. 2023). The distribution of stellar properties of FRB hosts has been found to be inconsistent with that of long gamma-ray bursts and superluminous supernovae, with a probable analogy with magnetars formed in core-collapse supernovae (Bochenek et al. 2021; Piro et al. 2021).

DSA-2000's impact

The existing sample of FRB hosts comprises of only 32 FRBs, which is not enough to draw any meaningful conclusions about the entire population and infer the properties of their sources to define their progenitor models. DSA-2000 will act as an FRB discovery and herald the era of sub-arcsecond scale FRB localizations. This will enable us to identify the stellar populations associated with the FRB progenitors and hence nail down their sources. Furthermore, the star formation histories of their host galaxies, obtained through stellar population modeling of their host galaxies while leveraging archival data and

available state-of-the-art observing instruments, will help constrain their delay-time distribution. This delay-time distribution will serve as a critical clue about the age of their progenitors. DSA-110, which was built as a prototype of the DSA-2000, has discovered and localized 30+ FRBs during the first year of its commissioning phase. Our sample of FRBs, together with the published sample, indicates that although FRBs are usually star-forming, they might as well originate from old stellar populations in elliptical galaxies (Sharma et al. 2023). Our preliminary constraints on the delay-time distribution suggest a striking similarity with short Gamma Ray Bursts and Core-Collapse Supernovae originating in interacting binary systems. The magnified sample size with DSA-2000 will help us answer the question of progenitors.

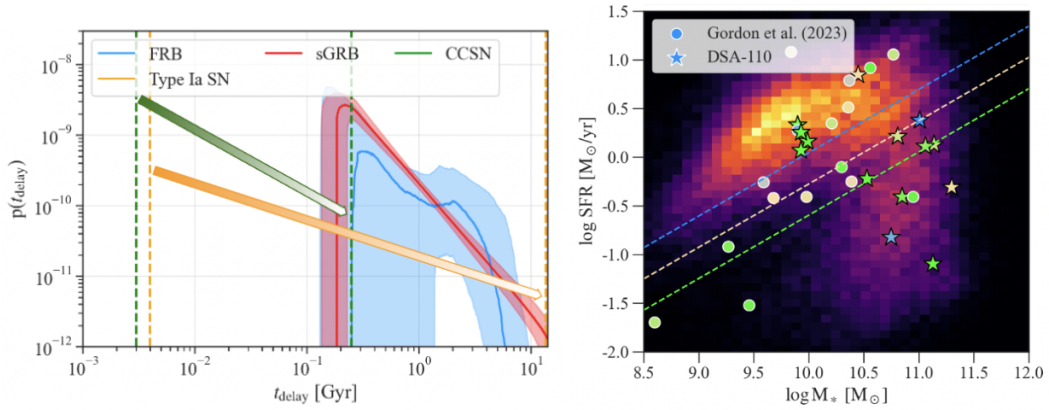


Figure 4.1: Key science results from DSA-110. Left: Constraints on the delay-time distribution of FRBs as compared to other transients suggest that the delay-time of FRB progenitors are quite wide and similar to short Gamma Ray Bursts and Core-Collapse Supernovae. Right: A comparison of FRB hosts to the background galaxies shows that majority of FRB hosts are star-forming.

System requirements / desired additions to baseline design

The existing system design is optimal for FRB science aimed in this particular science case.

4.4 Localizing Fast Radio Burst Sources Relative to Their Host Galaxies and Probing Cosmic Plasmas Using Radio Propagation Effects

Authors: James M. Cordes, Stella Koch Ocker, Shami Chatterjee, Cornell University

Summary

The fast radio burst (FRB) phenomenon offers a unique probe of cosmic plasmas along with the extreme physics of their sources. Current planning for radio arrays aims to localize large numbers of FRBs with sub-arcsecond precision yielding galaxy associations and redshifts through optical followup. Radio propagation effects (dispersion, scattering, scintillation, and Faraday rotation) provide the basis for constraining the locations of FRB sources and the interstellar media of their host galaxies, including circumsource environments. Radio scattering can indicate whether a source is embedded in or is in front of or behind the interstellar plasma of the host galaxy. For cases where interferometric localizations are infeasible or not precise enough to allow unique host identifications, radio scattering in concert with an analysis of the dispersion measure inventory (Milky Way, intergalactic medium, and host galaxy) provides coarse redshift estimates that can at least narrow the list of candidate galaxy associations. FRBs emitted at redshifts $z \gtrsim 0.25$ also sample the halos of intervening galaxies and galaxy clusters with the full suite of propagation tools.

DSA-2000 can provide a complete ensemble of observables for realizing this program for understanding both the large scale distribution of ionized gas in the universe and the peculiarities of host galaxies and circumsource environments. DSA-2000 can also provide a synoptic view of a large sample of FRB sources via multiple passes made with the sky survey and especially in the fields centered on millisecond pulsars, which will be revisited monthly as part of NANOGrav's long-wavelength gravitational wave program.

State of the Field

A key aspect of understanding FRB populations is whether the sources are young (located in star forming regions) or old (possibly outside host galaxies due to velocity kicks or originating in globular clusters). Localizations to sub-galaxy scales are required for this kind of study but also for fulfilling the potential for diagnosing plasmas in the intergalactic medium (IGM) and circumgalactic media (CGMs) using radio propagation diagnostics and other multiwavelength observations.

Source redshifts and positions in/near galaxies: Chromatic time delays of FRBs provide dispersion measures (DMs), the integrated free electron density (dominated by non-relativistic electrons), while multipath scattering, which probes small scale ($\ll$ AU) density fluctuations, is manifested in burst shapes and radio spectra. The line of sight inventory of DM for an FRB emitted at redshift z includes Milky Way, IGM, and host-galaxy contributions while the scattering time τ_d is dominated by interstellar media in the MW and host galaxy,

$$\text{Dispersion : } DM = DM_{\text{mw}} + DM_{\text{igm}}(z) + \frac{DM_{\text{h}}}{1+z}, \quad \text{Scattering : } \tau_d = \tau_{\text{mw}} + \frac{\tau_{\text{h}}}{(1+z)^3} \simeq \frac{\tau_{\text{h}}}{(1+z)^3}. \quad (4.1)$$

Coarse redshift estimates based on DM are made by subtracting the MW contribution based on Galactic models and by assuming or estimating the host contribution DM_{h} (in the host frame). Early assumptions that DM_{h} is generally small (e.g. $DM_{\text{h}} \lesssim 50 \text{ pc cm}^{-3}$) have become disfavored by cases with DM_{h} more than ten times larger ($\gtrsim 500 \text{ pc cm}^{-3}$). Estimates for DM_{h} follow from Balmer-line measurements of localized FRBs and by considering the $\tau_d(DM)$ relation based on Galactic pulsar measurements. The latter provides the basis for improved redshift estimates $\hat{z}((DM, \tau_d))$ based on both DM and τ_d because results to date indicate that

scattering in host galaxies is reasonably well calibrated by that in the MW.

FRB localizations with DSA-2000 and other telescopes will provide large redshift/host galaxy samples. However, the FRB source's position along the line of sight, which also matters for assessing any link to star forming regions, can be constrained by the scattering time τ_d , which depends strongly on geometric leveraging: τ_d is larger if the source is behind the galaxy and can be negligible if in front.

Circumsource and interstellar media: Some FRBs show spatially coincident 'persistent radio sources' and rapidly changing Faraday rotation and scattering indicative of circumsource plasmas at radii $\lesssim 1$ pc. Others show scattering clearly associated with the general ISM of the host galaxy. While temporal variations can signify source proximity, a detailed scattering/scintillation analysis can provide constraining distance offsets. Several FRBs display distinguishable scattering from both the MW (as scintillation frequency structure with $\delta\nu \sim \tau_{\text{mw}}^{-1}$) and the host (as pulse broadening, τ_h). Excessive host scattering can suppress MW scintillation by decreasing the coherence of the radiation incident on the MW. Manifestation of MW scintillation requires

$$\tau_h \tau_{\text{mw}} \lesssim \left(\frac{0.16 \text{ ms}}{\nu} \right)^2 \left(\frac{d_{\text{so}}}{1 \text{ Gpc}} \right)^2 \left(\frac{\text{kpc}^2}{L_h L_{\text{mw}}} \right) \quad (4.2)$$

for a source distance d_{so} in Gpc and screen distances $L_h = 1$ kpc and $L_{\text{mw}} = 1$ kpc from the source and observer, respectively. The presence of MW scintillations and an estimate for the path length L_{mw} yields an upper bound on L_h . Application to FRB 20190950, for instance, yields $L_h \lesssim 0.1$ kpc (Ocker et al. 2022, Ap.J., 321).

Methods that employ these analyses are required to extract maximal information about FRB sources, their host galaxies, and plasmas along the entire line of sight, whether or not FRBs are localized to host galaxies with measured redshifts.

DSA-2000's impact

DSA-2000 can provide all of the necessary observables (sans redshifts): spectro-temporal properties and polarization of bursts along with interferometric localizations. Burst dynamic spectra provide any information about scintillation structure (whether from the MW or host galaxy) and high time resolution burst profiles are needed to detect scattering broadening. Large samples of FRBs along different lines of sight are needed for addressing cosmic variance of the IGM and CGMs and interstellar variance of hosts. They are also needed for understanding the potential diversity of FRB source types. The multiple passes made in the synoptic sky survey and in high-cadence pulsar timing array observations allow investigation of dynamic changes in the circumsource environments of a large number of repeating FRBs. With $> 10^4$ FRB source detections with a sizable fraction of localizations of both one-off FRBs and repeating FRBs ($\sim 10\%$), DSA-2000 will be a premier instrument for the science of cosmic plasmas and the source probes that are needed for that science.

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

Commensal capabilities for FRB detections are required to exploit multiple sky passes. Time and frequency resolutions better than $100 \mu\text{s}$ and 100 kHz are needed with full Stokes parameters and in some cases flexible analysis afforded by buffered voltage data would be extremely valuable for measuring the finest scale scattering effects, which can be sub- μs in duration.

Table 4.1: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Polarization	IQUV for 2 MHz channels,	Higher resolution needed for scintillations and burst substructure studies.
	I only for all other channels	Voltage data availability ideal
continuum channels	605 channels, 0.7-2.0 GHz, 2.15 MHz resolution	Ditto
Cadence	1 every 4 months	Higher cadence or scheduled observations for long term FRB activity periodicities.
		Fields centered on MSPs for PTA/GW obs are ideal.

4.5 The No-Spin Zone for Fast Radio Bursts: Real or Only Apparent?

Authors: James M. Cordes, Shami Chatterjee, Ira Wasserman, Cornell University

Summary

In many respects, FRBs are similar to single pulsar pulses, though there are blatant differences in their dynamic spectra and, most strikingly, in the absence of any signature of rapid rotation in dense burst sequences that would be expected if the source is a rotating compact object. Given that some FRBs appear to originate from young magnetar-like objects and that Galactic magnetars show occasional spans of periodic emission with $P \lesssim 20$ s, there is a clear disconnect between the properties of the FRB and Galactic magnetar populations. Two plausible explanations are that the extreme conditions in and near FRB sources cause emission that is intrinsically aperiodic or that rapid periodicities are masked by other processes.

A large sample of bursts, many from repeating FRBs, that DSA-2000 and other telescopes can provide is required to understand FRB populations and their relation to older magnetars. Since periodicity detection (or its absence) is a key part of this program, adequate dwell times on individual FRBs are needed. Fortunately, DSA-2000 can provide these through commensal data acquisition.

State of the Field

Compact objects, especially young magnetar-like objects, are a focus of attention in many (but not all) FRB source models. It is natural to then expect see a signature of rapid rotation like that seen in pulsars and magnetars. What is seen, however, are the following:

1. Uncommon bursts with sub-second or sub-ms quasi periodicities are seen in a few cases but the vast majority of burst sequences show no hint of a rapid periodicity.
2. Long-periodic activity windows with 16 and 160 d periods have been seen for two FRB sources.

Expecting a manifestation of rapid spin follows naturally for two reasons: (1) Narrow millisecond bursts require compact emission regions that are known to arise from spinning compact objects; and (2) Precession and orbital motion are among the many candidate processes for long-period activity windows. Any precession, whether free (from a dynamic inertia tensor) or forced (binary interaction) of course requires a spin vector.

The absence of periodicities can be accounted for by two broad classes of explanation:

- A. Emission is from well outside the magnetosphere (light cylinder), perhaps from multiple sites, with no inherent periodicity tied to the spin of a central engine.
- B. Emission inside the magnetosphere:
 1. Multiple regions that emit independently, covering all of spin phase with sporadic emission from each region (e.g. poles of a multipolar magnetic field).
 2. Emission tied to spin phase that is delayed stochastically by propagation effects from circumspace plasma (refraction, reflections, absorption), including that associated with any binary companion.
 3. Precession can exacerbate 1. and 2. but needs to occur with a short period to decohere burst sequences of an hour or less.

If there is evolution from an FRB phase to a magnetar phase with radio periodicities, explanation A would imply a state change from an external (to the magnetosphere) process to an internal one. However, explanations B1-3 suggest a smooth evolutionary sequence that could be identified in large FRB samples. Distinguishing between A and B translates into a search for any ‘missing link’ type FRBs that would comprise evidence for B-type

explanations.

DSA-2000's impact.

Large samples of repeating FRBs with adequate dwell times can be provided by DSA-2000, primarily through commensal sampling during pointings for the sky survey and pulsar timing array observations. This aspect of FRB science does not require good localizations but repeating FRBs that are localized and have optical followup to yield Balmer lines and redshifts will provide complementary information about linkage to star forming regions or not

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

Repeat bursts are sometimes seen with rates as high as 100 hr^{-1} . Dwell times need to be long enough to capture $\gtrsim 10$ or more bursts in a given pointing (10 to 30 minutes) for a periodicity analysis. Time and frequency resolutions in the baseline reference design are adequate.

Table 4.2: Project requirements compared to DSA-2000 baseline reference design

DSA-2000 baseline reference design		match to project
Cadence	1 every 4 months	Longer dwell times useful. Cadence not critical except for FRBs showing long periodic windows (weeks to months)

4.6 Detecting strongly lensed fast radio bursts

Authors: Daniele Michilli

Summary

Strong lensing cosmography, i.e. measuring the delay between multiple images of a variable source that is strongly lensed, is a promising technique to measure properties of the universe such as the Hubble constant other than providing information about the lens itself (Treu, Suyu, and Marshall 2022). Fast radio bursts (FRBs) could improve the results of strong lensing cosmography by orders of magnitude (Li et al. 2018b). However, detecting strongly lensed FRBs is challenging due to the rarity of the phenomenon and the necessity to detect at least two images of the same burst separated by days. Here, an observing strategy with DSA-2000 is suggested to detect strongly lensed FRBs and enable their use for cosmography experiments.

State of the Field

Traditionally, AGNs have been used as lensed sources in cosmography experiments but their slow variability limits the measurement precision (Treu, Suyu, and Marshall 2022). Efforts are ongoing to use supernovae and gamma-ray bursts instead but they also have intrinsic limitations that affect the results (Treu, Suyu, and Marshall 2022). On the other hand, FRBs are ideal sources for this study (Li et al. 2018b). With only ~ 10 strongly lensed FRBs, the Hubble constant could be measured with a precision comparable to Planck (Li et al. 2018b), possibly independently on any lens model if an FRB repeats (Wucknitz, Spitler, and Pen 2021).

Currently, no lensed FRB has been detected, nor it is expected with current facilities (Connor and Ravi 2023b). Discovering a strongly lensed FRB requires the detection of a large number of FRBs at high redshift, only possible with a large field of view (FoV) together with a high sensitivity that current telescopes lack. In addition, at least two images of the same FRBs must be detected to measure their delay and these images will be separated by $\sim$ days. Currently, and for several years, the FoV of sensitive telescopes only covers a tiny fraction of the sky, making it highly improbable to detect both images blindly (Connor and Ravi 2023b). The following strategy is proposed to overcome this last challenge.

A lensed FRB will be identified by its association with a galaxy known to be lensed. Models of the lensed system will inform us of the expected delay of the additional images. Observing the FRB location around their expected arrival time will then allow us to detect them and refine the delay with great accuracy. This strategy requires precise localization of FRBs and a large catalog of lensed galaxies. The latter will become available within the next ~ 5 years when upcoming surveys such as Euclid and LSST will discover $\gtrsim 100,000$ lensed galaxies (Collett 2015), while DSA-2000 could even increase this number (Connor et al. 2022).

DSA-2000's impact

While strong lensing is a rare phenomenon, the large number of FRBs expected to be detected by DSA-2000 implies that a few strongly lensed FRBs could be detected each year. Moreover, the telescope's high sensitivity will allow us to find a distant population of FRBs, which have a higher chance to be lensed. The telescope's capability to precisely localize FRBs and its ability to track a sky position make DSA-2000 a perfect match for this project.

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

For the blind search of the first lensed image of an FRB, no additional requirements are necessary on top of the general FRB blind search. A localization $\lesssim 1''$ would allow us to distinguish whether the FRB comes from the background galaxy or the lens. A larger uncertainty would not prevent the project but would introduce many FRBs that may or may not be lensed with an increased challenge for following all of them up. If it will not be possible to search the whole telescope's FoV at maximum sensitivity for FRBs, it may be possible to form beams in the direction of cataloged lenses in the FoV. A FoV $\sim 10.6 \text{ deg}^2$ implies $\lesssim 100$ cataloged lenses visible at any given time, with a similar number of simultaneous beams necessary to track them.

Lens models will provide a time of arrival of the second FRB image with an uncertainty of ~ 1 day. Given its lower magnification factor, the large sensitivity offered by DSA-2000 would be ideal to detect it. In fact, DSA-2000 could also be used to target the second image of lensed FRBs detected by other instruments such as CHORD. Given the large uncertainty on the time of arrival, it would be ideal to use DSA-2000 to observe the same source for as long as possible during a day. It is expected that this will occur at most a few ($\lesssim 5$) times per year.

Table 4.3: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Spatial resolution	$3.5''$	$\lesssim 1''$

4.7 Pulsar Searching Forecasts for the DSA-2000

Authors: Myles Sherman, Vikram Ravi, Casey Law, Liam Connor, Jim Cordes

Summary

The DSA-2000 will implement a novel pulsar search strategy which leverages the continuum Cadenced All-Sky Survey (CASS) to target ~ 4000 beams containing unresolved sources without optical associations. Using this method, the search can be carried out with high resolution (0.1 ms) and a comparable sensitivity to the Arecibo telescope ($SEFD = 2.5$ Jy). The cadenced nature of the search (16×4 month epochs) will give the DSA-2000 a unique sensitivity to time-variable and accelerated pulsar binaries; population synthesis indicates the array could increase the known pulsar population by $7\times$, which will have an immediate impact on the capabilities of Pulsar Timing Arrays (PTA) and dense equation of state (EOS) experiments.

State of the Field

The Australia Telescope National Facility (ATNF) catalog currently holds 565 millisecond pulsars (MSPs) and 2760 canonical pulsars, 24 of which have neutron star binary companions and none of which have black hole companions. The majority of pulsars in the ATNF catalog, roughly ~ 2000 , were detected by the Arecibo and Parkes Telescopes, which have System Equivalent Flux Densities (SEFD) of 2.3 Jy and 28.6 Jy respectively (e.g. Parent et al. 2022, Manchester et al. 1996). Since the collapse of Arecibo, its sensitivity has not been recovered by comparable surveys. In comparison, the Green Bank Telescope has contributed 261 discoveries, while surveys by the Giant Metrewave Radio Telescope (GMRT), Effelsburg 100m Radio Telescope, Molonglo Observatory Synthesis Telescope (MOST), and Jodrell Bank Observatory have discovered a combined 291 (Bhattacharyya et al. 2016, Barr et al. 2013, Manchester et al. 1978, Stovall et al. 2014). The most recent boon to single-telescope pulsar searching has been the Five-hundred meter Aperture Spherical Telescope (FAST), operating at L-band and detecting a total of 262 pulsars through its first four years of operation (Han et al. 2021, Cruces et al. 2021).

The continued rise of radio interferometry has offered a new path to recovering the sensitivity of Arecibo, as the effective SEFD scales inversely to the number of antennas. The MeerKAT array (1.4 GHz), precursor to the Square Kilometer Array (SKA) has thus far discovered 23 new pulsars through the first 3 years of its TRAPUM survey, while the Canadian High Intensity Mapping Experiment (CHIME) Pulsar Survey (600 MHz) has detected 28, through its first 5 years (Clark et al. 2023, Amiri et al. 2021). The LOFAR array (135 MHz) has additionally detected 53 pulsars through its Tied-Array All-Sky (LOTAAS) survey (Sanidas et al. 2019). While these surveys do not match the sensitivity of Arecibo, they indicate the potential of large interferometers to detect more exotic species of pulsars like double-neutron stars, neutron-star black hole binaries, Redbacks, and Black Widows.

DSA-2000's impact

The DSA-2000's large $\sim 31,000$ square degree survey area, high time resolution down to ~ 0.1 ms, and Arecibo-like full-array $SEFD = 2.5$ Jy suggest it has the potential to significantly increase the number of known galactic pulsars through a dedicated periodicity search. The search will be commensal with the continuum Cadenced All-Sky Survey (CASS), and leverage its catalog of $> 10^8$ radio continuum sources in a novel search strategy. By removing any resolved continuum radio sources with optical or infrared

associations through cross-referencing with existing catalogs (e.g. Pan-STARRS, Legacy Survey), the DSA-2000 will identify and search only a subset of ~ 4000 beams per pointing likely to contain pulsars. By reducing the computational load in this way, the search can be conducted with higher resolution and full-array sensitivity. Population synthesis indicates that this survey method could detect 25,902 pulsars, or about 18% of the galactic population within the DSA-2000's survey area; this would increase the known population by $7\times$ and additionally recover pulsars that a blind periodicity search is insensitive to. The cadenced 16×4 month epochs additionally provide a unique sensitivity to time-variable pulsar systems affected by scintillation, nulling, or orbital modulation. Furthermore, the DSA-2000 will carry out an acceleration search, targeting sub-populations by varying the integration time and sampling time epoch-to-epoch. Increasing the population of MSPs will have significant impact on the timing efforts of Pulsar Timing Arrays (PTAs) and the efficacy of equation-of-state (EOS) experiments, while detection of exotic, accelerated binaries like Redbacks, Black Widows, and double-neutron stars will provide a more holistic view of pulsar formation channels.

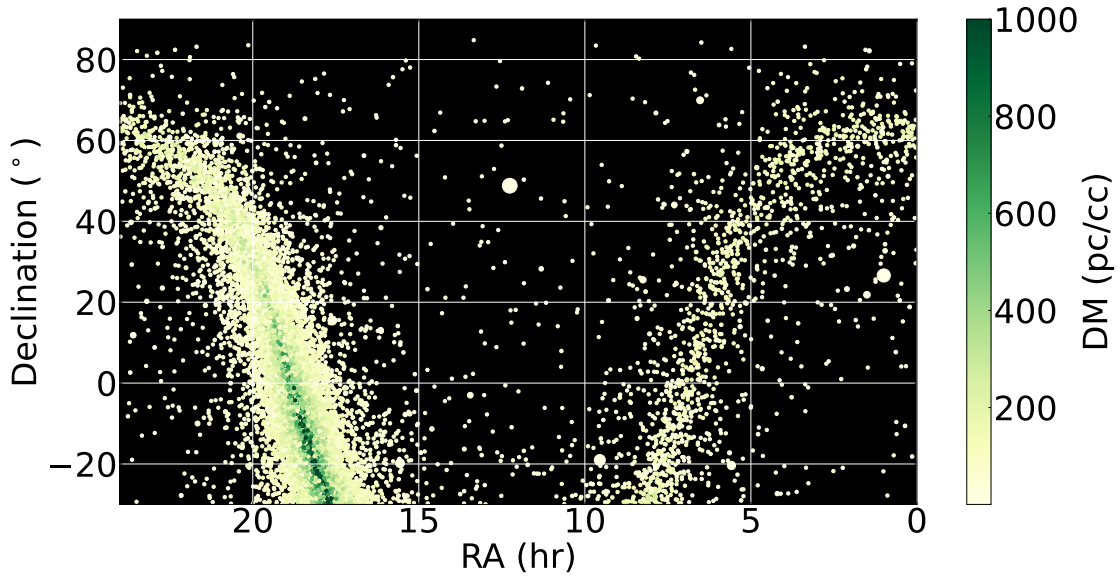


Figure 4.2: 25,902 simulated pulsars that the DSA-2000 is sensitive to through the CASS survey in conjunction with a periodicity search. The size of each point corresponds to its flux, while its color corresponds to its dispersion measure (DM)

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

The DSA-2000 can achieve this pulsar search with its 0.1 ms resolution and 134 kHz channels. It is likely that the search system will require a duplicated beamforming pipeline to allow for variation of relevant survey parameters. In addition, an initial 1 year epoch of the CASS with longer 45 minute pointings would be preferable before starting the 4 month epochs with 15 minute pointings in order to build up an initial catalog of continuum sources.

Table 4.4: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Declinations	$\delta > -31^\circ$	good, ideally all-sky
need for additional modes	N/A	variable sampling rate, channelization

4.8 Ultra-long period magnetars & magnetized mergers: A new population of neutron stars

Authors: Zorawar Wadiasingh, Alex Cooper, Paz Beniamini

Summary

Periodic windowing behavior, as (unexpectedly) discovered in some FRBs, is perhaps an important clue to the FRB radio mechanism or source requirements. Based on recent detections of candidate Galactic ultra-long period magnetars in radio surveys, a vast but as-yet undetected population of them likely exists, and implies they are much older than canonical magnetars. This bolsters the argument that they are related to periodically windowed FRBs. Future imaging radio surveys with DSA-2000 will likely discover many isolated ultra-long period magnetar candidates in our galaxy. Their existence and age also implies some will be involved in compact binary coalescences, e.g., neutron star-neutron star mergers. The large magnetic field of magnetars significantly enhances the orbitally-induced radio emission prior to merger. Such emission ought to be in principle discoverable due to dispersive delays of the radio emission, if localization and warning from high energy instruments or gravitational wave (GW) networks is promptly communicated to radio facilities. The radio horizon to such pre-merger emission is significantly larger than GW detectors and emission is expected in a large solid angle, meaning a small subset of apparently non-repeating FRBs may stem from compact object mergers. The pre-merger emission, if detected, also enables independent measurements of the merging neutron stars' magnetic field strengths, and the relativistic inspiral orbital dynamics for fundamental physics constraints.

State of the Field

Recent studies have reported on discoveries of Galactic ultra-long period pulsars (Caleb et al. 2022; Hurley-Walker et al. 2022; Hurley-Walker et al. 2023). These objects have periods of at least several tens and up to over a thousand seconds. They are likely highly-magnetized and magnetically-powered (i.e. magnetars) and could constitute the tip-of-the-iceberg for this new radio source class. The first discovery on a potential member of this class was reported by Hyman et al. 2005. However, it proved challenging to interpret and confirm the nature of the object at the time. The recent discoveries have been enabled by new radio transient surveys using imaging methods (as DSA-2000 will do), and rejection of prejudice (theoretical and observational) for sources beyond the conventional pulsar curvature pair cascade death line. Several recent developments demolished incorrect priors for sources beyond the radio death lines. First, theoretical arguments in 2019 by Wadiasingh et al. 2020 favored longer-period magnetars as potential FRB sources. Observationally, periodically windowed FRB activity reported for FRB 20180916 by (Chime/Frb Collaboration et al. 2020b), and subsequent possible interpretation of this source as an ultra-long period magnetar (ULPM) occurred rapidly in early 2020 (Beniamini, Wadiasingh, and Metzger 2020). These two developments, as well as the existence of a 6.67 hr spin period (radio-quiet) magnetar in supernova remnant RCW 103, reinvigorated image-domain radio transient searches for such objects within the Milky Way. Subsequently, three discoveries were reported within two years. Hurley-Walker et al. 2022's object, in particular, attained 40-50 Jy flux densities when it was active, and would have been bright enough to be detected by Karl Jansky himself!

The nearby distances of these objects imply a large extant population numbering in the tens of thousands in our galaxy (Beniamini et al. 2023) whose detection horizon is vastly improved with DSA-2000 (see Fig. 4.3). Beniamini et al. 2023 estimated DSA-2000 will detect at least hundreds of such objects. This may well prove to

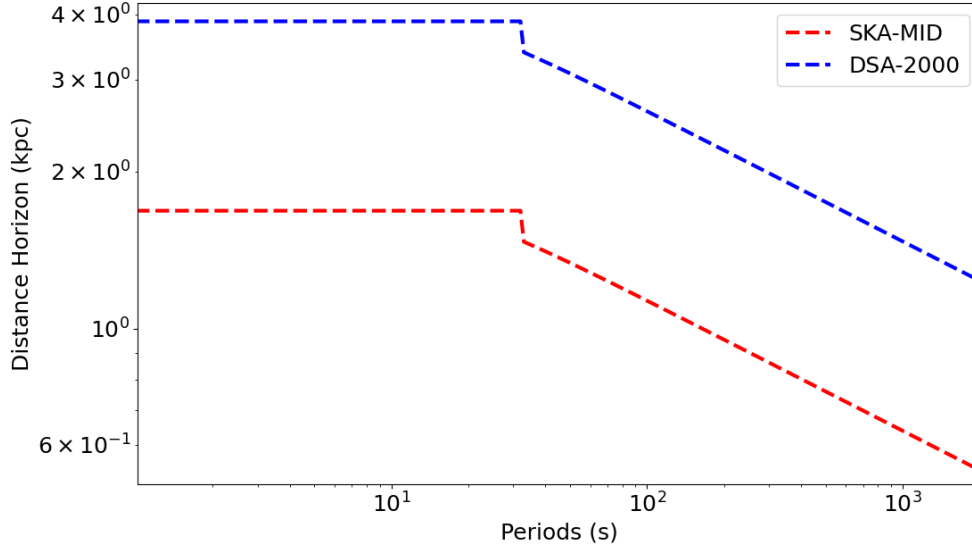


Figure 4.3: Distance horizon for a putative long-period pulsar similar to PSR J0901–4046 assuming a survey with pointings of 3600 seconds. Adapted from Beniamini et al. 2023. Given the high source density of such active objects estimated in Beniamini et al. 2023, a DSA-2000 survey with such depth will detect $O(100)$ such sources.

be overly conservative, and the true number in the next decade could exceed this by a large factor. The source densities detailed in Beniamini et al. 2023 also imply older ages > 100 kyr for the objects, implying widespread survival of magnetar-like core magnetic fields, well beyond the typical (crustal) magnetic field decay timescales inferred for regular magnetars. This has exciting implications for precursor radio emission in binary neutron star mergers (see below).

There are several outstanding questions that DSA-2000 will help answer:

- How many ULPMs are out there? How are they related to FRBs? Are they related to the Galactic center burper?
- What is their Galactic latitude distribution? What are their inferred ages and active radio lifetimes? What is their dominant formation channel?
- What is their period distribution?
- What is the radio luminosity function of ULPMs?
- Are there QPOs or spiky features in ULPM radio pulsations?

Precursor emission from compact object mergers involving at least one neutron star is predicted to arise from the magnetospheric interaction between merging components (Most and Philippov 2022a), as well as through resonant crust shattering (Neill et al. 2022). Magnetospheric interaction typically predicts emission profiles modulated by the orbital phase, allowing measurements of the equation of state of merging neutron stars complementary to gravitational waveforms. Although the evolutionary channel to produce theorized ultra-long period magnetars is uncertain, these sources may be much older than observed Galactic magnetars (Beniamini et al. 2023), and may represent a non-negligible fraction of merging neutron stars. Moreover, fast channels for neutron star mergers likely exist (Beniamini and Piran 2023). Coherent radio counterparts in particular represent the most likely candidate for detections, owing to the sensitivity and field-of-view of radio telescopes. Searches for pre-merger radio emission have thus far been spearheaded by low-frequency radio telescopes, which can rapidly slew to targets, through triggered observations with MWA of sGRBs (Tian et al. 2022) and gravitational

wave events (Tian et al. 2023) proving particularly constraining. The DSA-2000 FRB survey (along with the SKA), will be a leading instrument in blind searches for pre-merger coherent emission (Cooper et al. 2023), with an estimated detection rate of $15 B_{s,12}^3 \eta_{r,-2}^{3/2}$ pre-merger events per year for the stated surface magnetic field and radio efficient parameters (Fig. 4.4). Furthermore, the DSA-2000 horizon to pre-merger emission is $3.7 \text{ Gpc } B_{s,12}^3 \eta_{r,-2}^{3/2}$, (Cooper et al. 2023) meaning the detection of such emission could allow us to probe gravitational wave events at much larger distances than accessible with the current generation of gravitational wave detectors. These expressions assume a Poynting-flux like scaling for the radio luminosity; if a voltage-like scaling is realized (as observed in Galactic radio pulsars), the detection rate and horizon are modified, which may also be probed by DSA-2000.

For triggered observations, the relatively large field of view of DSA-2000 means gravitational wave event localization regions can be efficiently probed. This is particularly important as the median localization region for a five detector network (including LIGO India) is expected to be 9 – 12 square degrees (Corsi et al. 2019). Pre-merger alerts are expected to be issued during the next gravitational wave observing run (Magee and Borhanian 2022). Despite the expectation that localizations will initially be poor, as they improve the field-of-view of DSA-2000 will be crucial for probing coherent radio emission produced shortly before the merger. An additional advantage of such detections would be the ability to obtain a sample of events with known redshifts and measured dispersion measures (DMs), that are independent of the FRB population. Considering the different environment of FRBs and BNS mergers, such a sample will enable to obtain a less biased estimate of the DM contributions of different host galaxy types and therefore improve our accuracy in modeling the contribution due to IGM propagation. This will enable to better utilize DM measurements for studying cosmology.

DSA-2000's impact

DSA-2000 will detect more ultra-long period magnetars and pulsars in our Galaxy, and help determine if they are related to FRBs. It will determine their source density, constrain their formation channel and ages. It will also determine whether they can be involved in compact binary coalescences via pre-merger precursor emission, and their delay time distribution. It will also determine if the horizon and rates exceed that of LVK, and if the radio luminosity scales as voltage or Poynting flux.

System requirements / desired additions to baseline design

N/A

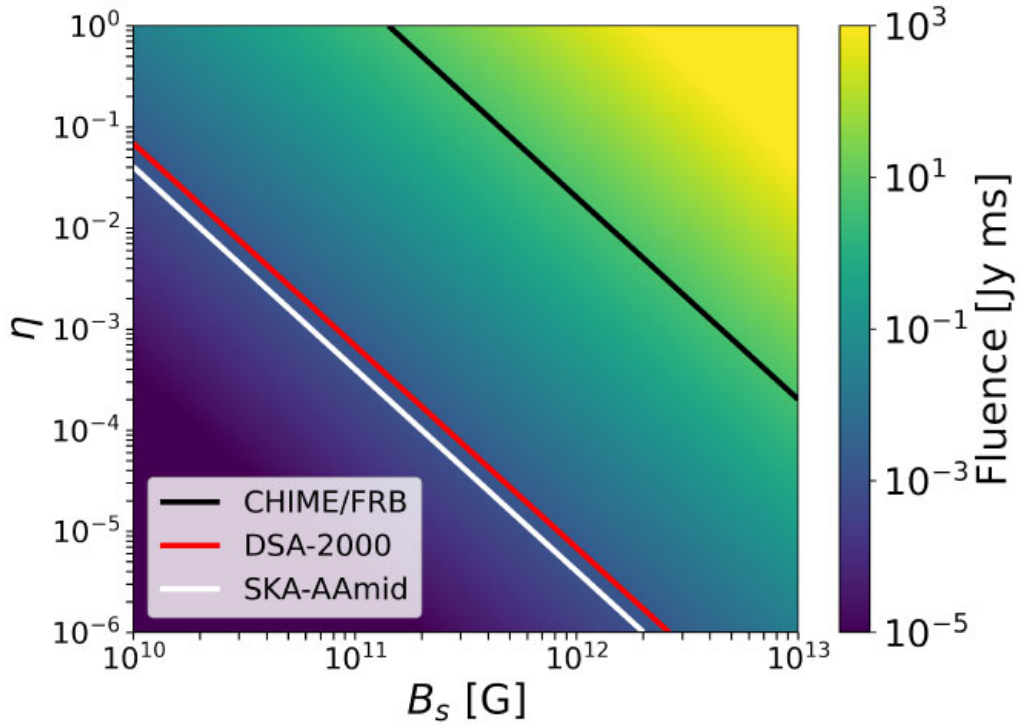


Figure 4.4: The fluence (in the last 3 ms) of a BNS merger at 100 Mpc as a function of radio efficiency and primary component's magnetic field. The accessible parameter space is to the right of the red line for DSA-2000. For high magnetizations, very constraining limits on radio efficiency can be obtained. The calculation here assumes a Poynting-flux scaling of radio luminosity – different contours will be realized for a voltage scaling. Adapted from Cooper et al. 2023, where the authors predict an unbiased DSA-2000 FRB survey should detect $15 B_{s,12}^3$ pre-merger events per year, where based on a volumetric NS-NS merger rate of $10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$.

4.9 Search for Technosignatures with the DSA-2000

Authors: T. Joseph W. Lazio (Jet Propulsion Laboratory, California Institute of Technology), Greg Hellbourg (California Institute of Technology) & Vikram Ravi (California Institute of Technology)

Summary

For millennia, the question has been posed of whether there are other worlds inhabited by other sentient beings. Today, the number of known extrasolar planets numbers in the thousands, and a long-term goal posed by the Pathways to Discovery Decadal Survey is to characterize nearby extrasolar planets for signatures of biological activity, “biosignatures.” However, biosignatures cannot distinguish between a planet hosting single-celled organisms or an advanced civilization. The DSA-2000 will be able to conduct searches of nearby extrasolar planets for signatures of technology, “technosignatures,” indicative of a civilization with technology levels comparable to that of present-day humanity. More distant civilizations with greater energy uses also might be able to be discovered.

State of the Field

The radio frequency Search for Technosignatures aims at detecting extraterrestrial transmissions of artificial origin, and set limits to the development of intelligent life throughout the Universe. The search space spans 9 dimensions (Time, Frequency, Bandwidth, Sensitivity, Polarization $\times 2$, Space $\times 3$) and has been sparsely explored over the past 60 years. While the effort has so far been unsuccessful, it benefits from a strong engagement from the astronomical community who values the importance of searching for unexpected or anomalous signals. Hundreds of observing programs have been conducted since its inception, each spanning a narrow subset of the large search space.

DSA-2000's impact

The DSA-2000 represents a unique opportunity to conduct a commensal search for technosignatures covering a large searching parameter space with no baseline reference design changes.

Sensitivity : *Figure 4.5 demonstrates that the DSA-2000 could provide a powerful telescope for identifying technosignatures within the solar neighborhood, even at the native spectral resolution of 134 kHz.*

Signal search : *The program will search in real-time for energy sparsity on the 5 millions FRB search beams at a 1 ms / 134 kHz resolution for each pointing over the full 1300 MHz frequency span of the instrument. A tradeoff between spatial coverage and time resolution is possible using the pulsar search beams.*

10 kpc survey : *We additionally propose to conduct a targeted survey of a sample of objects located within 10 kpc from the Earth extracted from the Gaia catalog. This survey will use the idle pulsar timing voltage beams. Up to 4 voltage beams are available in each pointing, which allows up to $4 \times 8,600 = 34,400$ objects to be surveyed at a high frequency resolution.*

Cadence : *The cadenced observing strategy that the DSA-2000 will follow is appropriate for the Search to distinguish technosignatures from terrestrial interference. It also supports the assessment of time structure of potential extra terrestrial transmissions.*

RFI : *The quiet radio environment simplifies the Search and reduces the false detection rate.*

Offline search : *The Search will also extend into the image domain to search for bright transmitters*

(pixels) cross-referenced with astronomical objects catalogs.

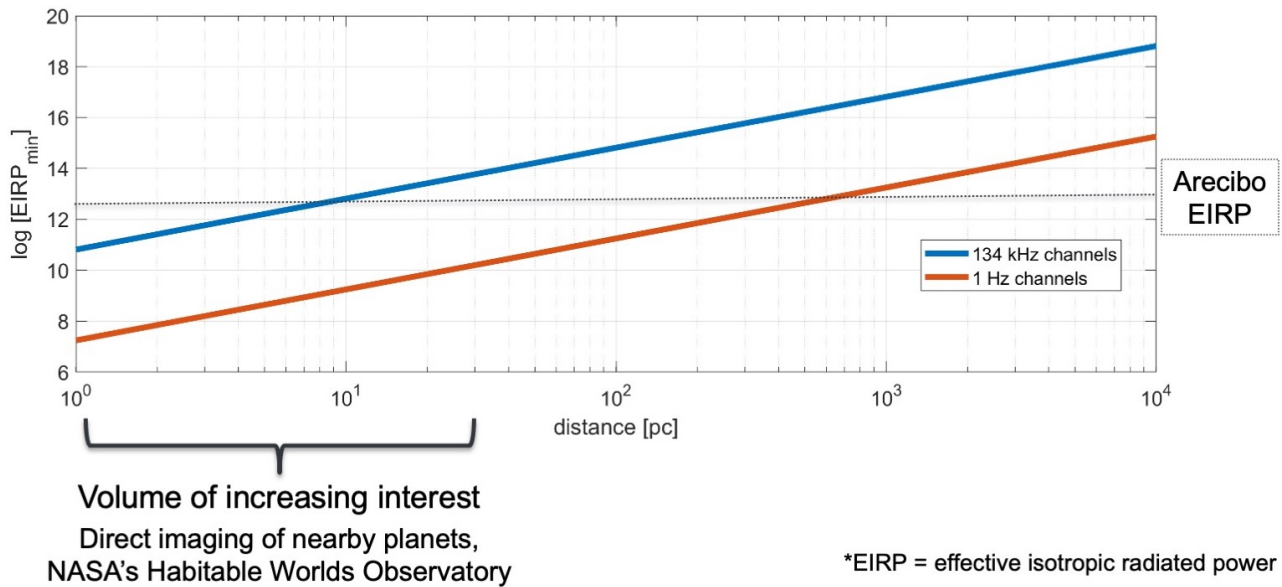


Figure 4.5: The DSA-2000 will be sensitive enough to search for radio wavelength signatures of technology at levels comparable to current terrestrial capabilities to at least 10 pc. This volume near the Sun will be of considerable interest in the next decades as planets within it will be the subject of considerable scrutiny for signatures of active biology and targets for direct imaging, potentially including the future Habitable Worlds Observatory. The blue line shows the sensitivity achieved with the default 134 kHz spectral resolution planned for the pulsar and fast radio burst (FRB) backend. The orange line shows the sensitivity that could be achieved with the traditional 1 Hz spectral resolution used commonly in radio wavelength technosignature searches. The dotted horizontal line shows equivalent isotropic radiated power (EIRP) of the Arecibo Observatory's 900 kW planetary radar system, had it transmitted within the DSA-2000 frequency range.

System requirements / desired additions to baseline design

No addition to the baseline design is necessary to conduct the Search. The real-time beam data will be captured following a digital design similar FRB subsystem. Additional compute capabilities will be required to search the individual beams, for which the cost is under study and dependent on the selected search algorithms.

Offline image-base searches will operate on the raw survey data products and will not require additional capabilities.