Discovering Exotic Pulsars and Transients with VLASS and Time Domain Surveys

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1 Introduction

Two of the areas of unusual discovery potential highlighted in the *New Worlds, New Horizons* decadal-survey report are time-domain and gravitational wave astronomy. Key science-frontier questions include the dynamic radio sky and the basic properties, origins, and evolution of compact stellar remnants—neutron stars and black holes. We propose to use the Very Large Array Sky Survey (VLASS) program as part of a "Finding Survey with Follow-up" methodology for discovering compact objects and novel classes of transient sources that together impact these questions.

Standard time-domain surveys of pulsars and fast transients (i.e., single pulse signals with characteristic times $\lesssim 10$ s) have been extraordinarily successful in finding pulsars, including those that led to the Nobel prize for demonstrating the existence of gravitational waves (Hulse & Taylor 1975) and to the discovery of the first extra-solar planets (Wolszczan & Frail 1992). However, such blind surveys are telescope-time and processing intensive, and they will miss many objects because the temporal modulations that search algorithms rely on will be quenched by interstellar scattering and by incomplete orbital compensation. Candidates are also masked by insidious radio frequency interference that is getting worse over time.

The proposed approach to finding exotic objects takes advantage of the vast increase in interferometric sensitivity enabled by the VLA, and requires a survey at lower frequencies (1–2 or 2–4 GHz) with high resolution ($\sim 1''$) and multiple sky passes that covers the entire sky or at least the Galactic plane. (Desired and acceptable survey parameters are summarized in §5, Table 1.) Candidates will be pre-selected with the VLASS using radio compactness and spectral characteristics, along with cross-catalog winnowing based on multiple wavelength surveys (optical and infrared along with high-energy) and other indicators. Computation-intensive search techniques will then be applied to targeted time-domain observations of only the selected candidates. Such a "Finding Survey with Follow-up" (FS+F) methodology is particularly efficient for populations such as pulsars that have low surface density and expensive follow-up (or blind search) requirements. FS+F is a key strategy for future telescopes, including MeerKAT and the SKA, where the computational demands of a blind survey (with sufficient phased array beams to tile the primary beam field of view) are huge and currently infeasible. Instead, the hybrid approach provides survey efficiency, robustness to interference, and sensitivity to exotic objects that are missed in standard pulsar surveys: double neutron star (DNS) binaries with orbital periods less than an hour, elusive pulsar-black hole binaries, and pulsars with sub-millisecond spin periods, should they exist. The detection phase space will also include transient sources with a broad range of time scales.

2 Why find more exotic pulsars and transients?

There are multifold motivations for large scale surveys to add to the known population of radio pulsars and transient sources. We highlight a few below:

- **Unique Opportunities for Testing General Relativity:** Pulsars with NS companions have allowed the highest precision tests for many aspects of GR and its foundations, such as the Equiv-

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alence Principle, which has been tested with pulsar/white-dwarf binaries (Gonzalez et al. 2011). The best object so far is the double pulsar J0737−3039 (Burgay et al. 2003; Lyne et al. 2004) owing to its short 2.5-hr orbital period (Kramer et al. 2006b). Yet shorter-period objects should exist with accordingly much larger post-Newtonian effects. DNS binaries have radio-observable lifetimes determined either by the gravitational wave (GW) inspiral time or by the radio emission shutting off as the pulsar spin gets too long, which end up being comparable. The orbital period distribution scales as $P_{\rm orb}^{5/3}$. The number of short-period binaries with $P_{\rm orb} \le 2.5$ hr (the current shortest for a DNS binary) is in proportion to long-period binaries with 7 hr $<$ $\rm P_{orb}$ $\le$ 10 hr as $R_{s/l} \approx (2.5/10)^{8/3} = 0.025$, so with $\sim$ 2000 DNS binaries in the Galaxy, there should be about 50 with $P_{\rm orb} \le 2.5$ hr and 5 with $P_{\rm orb} \le 1$ hr. Discovery of such objects is highly desirable for the GR payoff. Given their sparseness, these objects are generally going to be far from the Sun, implying strong selection effects in periodicity surveys due to orbital smearing and interstellar scattering.

- **Constraining the Equation of State (EoS) of Supra-nuclear Matter:** Measurements of two or more post-Newtonian orbital perturbations, such as apsidal advance and the Shapiro delay, allow individual masses to be solved for and have provided precise mass measurements (to $10^{-2}M_\odot$ precision) extending up to $2M_\odot$ in DNS binaries (e.g., PSR J1614−2230; Demorest et al. 2010), large enough to rule out many EoS and constrain the possible roles for quark matter. Probing the full NS mass distribution and extending it to higher masses is a primary goal of ongoing surveys.

- **Neutron Stars as Sources of Gravitational-Waves (GWs):** The merger rate of DNS binaries in the Milky Way is scaled to cosmological distances in order to predict the event rate of chirped signals detectable by Advanced LIGO and VIRGO (e.g. O'Shaughnessy et al. 2008). Only four of the currently known DNS binaries will merge within a Hubble time due to GW emission; any new discoveries will tighten up the event rate prediction (e.g., Burgay et al. 2003).

- **Pulsars as Detectors of Gravitational Waves:** The goal of pulsar timing arrays (PTA) is to detect long-wavelength (nanohertz) GWs produced by merging supermassive black-hole binaries and possibly by cosmic strings (e.g., Demorest et al. 2013). Only the most spin-stable MSPs are suitable for this enterprise and more MSPs are needed to provide the signal-to-noise ratio needed for a coherent analysis of the array of MSPs (e.g., Burt et al. 2011). These goals are being pursued by PTA groups in North America (NANOGrav), Australia, and Europe; the groups have begun to federate as the International Pulsar Timing Array.

- **Discovery and Timing of a Pulsar-Black Hole Binary:** While DNS binaries with at least one active pulsar are scarce ($\sim$2000 in the Galaxy), NS-BH binaries with an active radio pulsar are even more so, of order a factor of ten less numerous according to population synthesis computations (e.g., Lipunov et al. 2005). The payoff from the discovery of a NS-BH binary is extraordinary, allowing space-time to be probed in the strong-gravity regime through a potentially richer set of timing perturbations than allowed by DNS binaries (including gravitational lensing of the pulsar).

- **Understanding Intermittency:** Intermittent pulses are now increasingly found as a byproduct of pulsar surveys and range from one-off events to periodic but highly modulated signals that are from pulsar-like objects. The collection of events and objects found through individual bursts are loosely referred to as rotating radio transients (RRATs; McLaughlin et al. 2006; Deneva et al. 2009) and in some cases as "fast radio bursts" (FRBs; Lorimer et al. 2007; Thornton et al. 2013) that are one-off events (so far) with dispersion measures too high to be accounted for by the Milky Way interstellar medium. In addition, some pulsars show intermittency on timescales from days to years (e.g. Kramer et al. 2006a; Camilo et al. 2012). An unbiased search with multiple observation passes may reveal additional empirical classes of transients and new source types.

3 Blind Time-Domain Surveys *vs.* a Hybrid Imaging/Periodicity Survey

The ultimate goal for pulsar surveys is to conduct a **full Galactic census**. This will enable us to understand the core-collapse process and the evolution of compact stellar remnants through the entire population, as well as to find rare, exotic objects amid the totality of $\sim 2\times 10^4$ canonical (i.e., non-recycled) pulsars, about the same number of MSPs, ∼200–2000 DNS binaries, and $\lesssim 100$ pulsar-BH binaries. A large majority of the ≈ 2200 known pulsars have been discovered through traditional searches for periodicity P and pulse dispersion measure DM (hereafter P–DM searches) of the Galactic plane (e.g., $|b| \leq 5^\circ$), but such blind surveys with current/next-generation telescopes cannot sample a large enough Galactic volume to undertake a full census. Moreover, they are biased, and may be missing the most interesting objects.

P–DM Searches: The ionized interstellar medium of the Galaxy scatter-broadens pulses irrevocably, posing a challenge for pulsar searches. Therefore, the highest yielding pulsar surveys have been made at a frequency $\nu \sim 1.5$ GHz using the Parkes (64m) and Arecibo (305m) telescopes. This frequency optimizes the conflict between maximizing pulsar flux densities, which typically (though not exclusively) decline at higher frequencies $S_\nu \propto \nu^{-1.6}$, and minimizing interstellar scattering, which broadens pulses by an amount $\propto \nu^{-4}$. However, the compromise higher frequency reduces sky coverage for a given amount of survey time (lower target flux and smaller beam area) leading to the push for multi-beam receivers (13 beams at Parkes, 7 at Arecibo) and corresponding data storage/reduction challenges. Currently, there are large scale pulsar surveys in progress at all large single-dish radio telescopes, including, for example, the Arecibo Pulsar ALFA survey (PALFA; e.g., Cordes et al. 2006) and the GBT North Celestial Cap pulsar survey, (e.g., Kaplan et al. 2012).

Hybrid FS+F Searches: Radio FS+F surveys have a long heritage (e.g. Cameron et al. 2011). Historically, the radio source 4C 21.53 was discovered through synthesis imaging and identified as a pulsar candidate due to its compactness and steep radio spectrum (Purvis 1983). Traditional pulsar surveys did not identify any periodic signal (Hulse & Taylor 1974); instead it required a novel pulsar survey with significantly higher time resolution to identify this source as PSR B1937+21, the first millisecond pulsar (Backer et al. 1982).

However, exploiting this technique on larger scales has been difficult. Imaging surveys have typically lacked sufficient sensitivity and resolution to be competitive. For example, Kaplan et al. (2000) identified 74 bright ($S_{365} > 200$ mJy), compact ($\theta < 25''$), radio sources with steep spectral indices ($S_\nu \propto \nu^\alpha$; $\alpha < -1.5$) out of ∼30,000 sources common to the 1.4 GHz NVSS (Condon et al. 1998) and the 365 MHz Texas survey (Douglas et al. 1996), of which 6 were known pulsars and 16 were unresolved ($\theta < 0\overset{''}{.}2$) but remained unidentified. Likewise, Crawford et al. (2000) cross-matched NVSS and FIRST to catalog 92 bright ($S_{1400} > 15$ mJy) unidentified sources with fractional linear polarization above 5%. These sources were followed-up with a 610 MHz radio periodicity search, with no detections. Most of these sources are likely compact radio galaxies, as revealed by deeper and higher-resolution follow-up observations.

Instead, observations at other wavelengths have stepped up to the plate. A highly successful example of the FS+F strategy is the search for pulsars in the *Fermi* unidentified gamma-ray source catalog. From ∼300 unidentified *Fermi* sources with low gamma-ray variability and pulsar-like spectra, radio P–DM searches have detected 4 canonical pulsars ($P_{\rm spin} \sim 1$ s, $B_{\rm p} \sim 10^{12}$ G) and over 50 MSPs ($P_{\rm spin} \lesssim 10$ ms, $B_{\rm p} \sim 10^8$ G) (Ray et al. 2012). However, this large increase in known MSPs is limited to nearby, energetic pulsars and does not sample the whole population.

Why should radio FS+F work now? The lack of new pulsars in previous radio FS+Fs can be chalked up to insufficient resolution ($\theta \approx 25'',\ 5''$) and low sensitivity ($S_{1400} \approx 15,\ 20$ mJy): given the luminosity function of pulsars, we just do not expect many new objects with flux densities

$> 15\,\mathrm{mJy}$. Now, though, the upgraded capabilities of the Jansky VLA and available computational power allow a radio point source catalog of sub-mJy sources with a resolution of $\approx 1''$. Coupled with greatly expanded capacities for multiwavelength cross-catalog filtering, an effective hybrid approach is now feasible.

Comparing P–DM and FS+F Surveys: Imaging surveys measure time-averaged flux densities that are largely unaffected by interstellar scattering and orbital smearing, and therefore do not select against extremely small spin and orbital periods. P–DM searches, by contrast, lose sensitivity due to pulse smearing from interstellar scattering and orbital motion, especially for short spin periods. We define the detection threshold $S_{\rm min,1} = mS_{\rm sys}/\sqrt{n_{\rm p}BT}$ for an $m\sigma$ detection, a system-equivalent flux density $S_{\rm sys}$, $n_{\rm p}$ polarization channels, bandwidth B, and integration time T. For an imaging survey, $S_{\rm min,1}$ is the threshold for a point source, while for a P–DM search it is the sensitivity for a single harmonic in the Fourier transform of a time series. Blind P–DM surveys involve huge numbers of statistical trials and require larger values of $m \approx 10$ to limit false positives compared to $m = 5$ for an imaging survey. Periodicity searches employ summing of harmonics to decrease the threshold to $S_{\rm min,N_h} \approx S_{\rm min,1}/\sqrt{N_h}$, where N_h is inversely proportional to the pulse duty cycle $= W/P \sim 0.05$ (W = pulse width). All else being equal, a periodicity search is more sensitive for pulsars with a small duty cycle, but pulse broadening effects (scattering and orbital modulation) increase W and reduce N_h. Severe broadening quenches even the fundamental spin frequency, and radio frequency inteference can mask any signal in selected period ranges.

Interstellar Scattering: Turbulence in the ionized interstellar medium (ISM) scatters radio waves into a “seeing” angle $\theta_{\rm sc} \propto \lambda^2$ that is a strong function of distance D (Rickett 1990). Scattering from multipath propagation also smears a temporal delta function into an asymmetric shape with width $\tau_{\rm sc} \sim D\theta_{\rm sc}^2/2c \propto \lambda^4$ (where c is the speed of light). The pulse broadening time can range from sub-microsecond to many seconds. This effect cannot be corrected for in P–DM surveys and dramatically reduces the sensitivity towards pulsars when $\tau_{\rm sc} \gtrsim W$, as illustrated in Figure 1.

These results indicate that short-period pulsars will be completely quenched for locations in at least half of the Galaxy and even known partially recycled pulsars in DNS binaries (with periods 20–100 ms) will be strongly selected against in much of the Galaxy. The recycled pulsar in the famous double pulsar binary, for example, with $P = 22.7$ ms and a “pseudo-luminosity[1]” $L_p = 2.1$ mJy kpc^2, is relatively near to us at 1.15 kpc. If placed at 8 kpc toward the inner Galaxy it would have been missed due to a combination of inverse-square law and scattering effects. The Hulse-Taylor binary pulsar ($P = 59$ ms, $W = 10$ ms, $D = 7.1$ kpc) is more luminous and could be detected to ~ 21 kpc with Arecibo if scattering were not an issue. However, pulse broadening limits the detectable distance to $D_{\rm max} \approx 10$ kpc for directions toward the inner Galaxy. P–DM surveys are thus luminosity limited for nearby pulsars where the intrinsic pulse width dominates scattering. However, when the opposite is true, they become scattering limited. The transition between the two regimes clearly depends on the pulse width that, in turn, is smaller for shorter spin periods, and on line of sight through the Galaxy. At 1.5 GHz, Arecibo surveys become scattering limited at distances $D \gtrsim 6$ kpc for 1.5 ms pulsars and only 3 kpc for $P = 0.5$ ms.

In contrast, at 1.4 GHz the angular broadening $\theta_{\rm sc} \lesssim 0.''1$ in almost the entire Galactic plane (Figure 1). With VLA A-array resolution $\sim 1.''3$, the effects of ISM scattering are negligible for imaging surveys and the maximum detectable distance of point sources depends only on inverse square law effects.

Orbital Smearing: Pulse smearing from orbital motion also reduces the sensitivity of a P–DM search. Unlike scattering, orbital modulation smearing can be corrected if all five Keplerian param-

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[1] The pulsar community defines the pseudo-luminosity as the period-averaged flux density $\times D^2$.

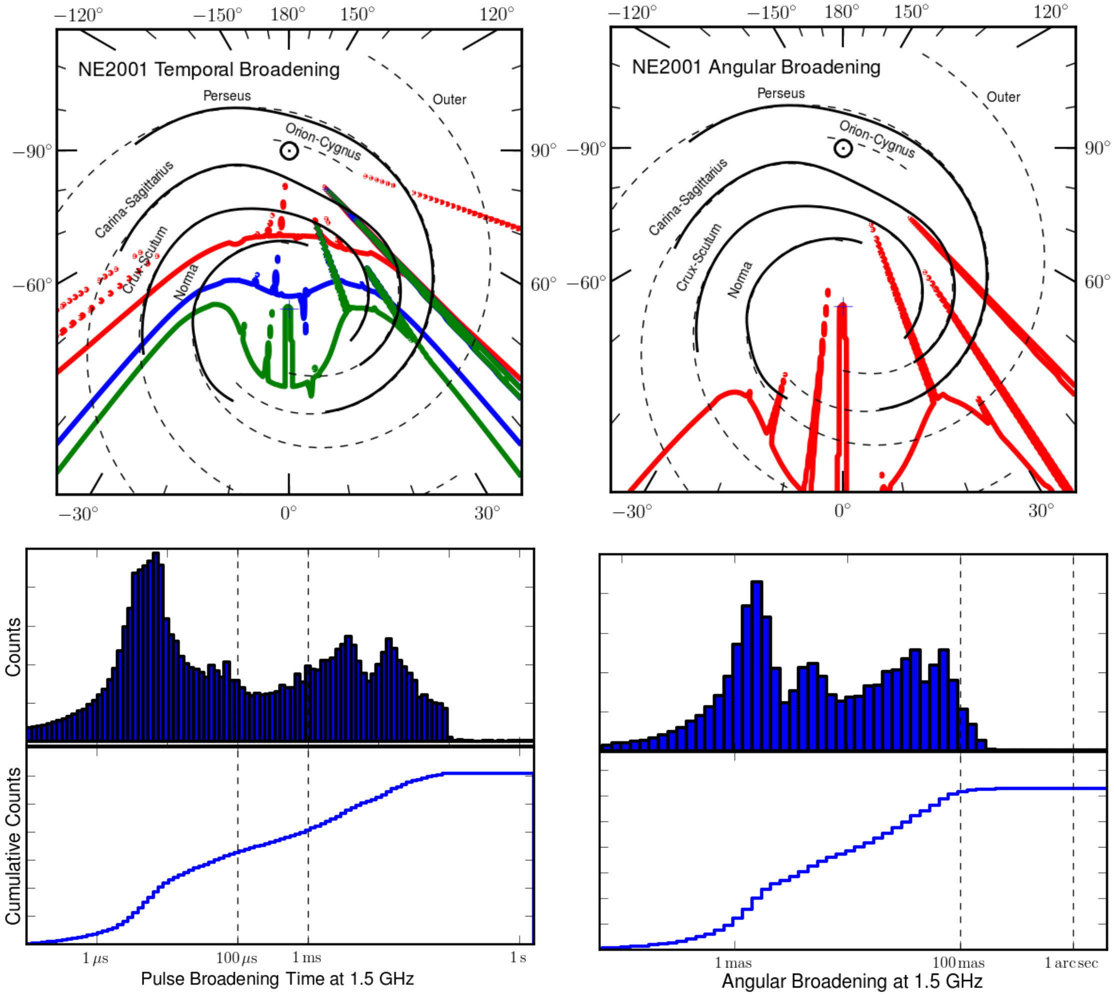

Figure 1: *Demonstration that time-domain surveys (i.e., periodicity and single-pulse searches) are impacted severely by interstellar scattering while imaging surveys are not.* **Bottom panels**: Histograms of pulse broadening time (left) and angular broadening (right) obtained by using the NE2001 electron density model (Cordes & Lazio 2002) for lines of sight that sample the entire Milky Way, and scaling results to 1.5 GHz. **Top panels**: projection onto the Galactic plane of the pulse broadening (left) and angular broadening (right). Spiral arms are designated with dashed lines (NE2001) and solid lines (Taylor & Cordes 1993). For pulse broadening (left), **red, blue, green contours** correspond to 1, 10, and 20 ms of smearing from scattering. For angular broadening (right), the red contour corresponds to $0.1''$. The narrow extensions pointing towards the Sun are due to strongly scattering HII regions in the NE2001 model. Pulse broadening will degrade the sensitivity of time-domain surveys for about half of the Galaxy for pulse widths of 0.1 to 1 ms and smaller. However, angular scattering will be less than $0.1''$ for almost the entire Galaxy except for directions within about 15 arcmin of the Galactic center ($\ell = 0°$).

eters describing the orbit can be determined, but an 8-parameter search (P, DM, duty cycle, and Keplerian parameters) is computationally infeasible and increases the number of statistical trials enormously, requiring a larger detection threshold. For some binaries, the orbital modulation can be removed with an approximate "acceleration" search (4 parameters: P, DM, duty cycle, acceleration) which is effective only for integration times much smaller than the orbital period (i.e., $T \lesssim 0.1 P_{\rm orb}$). Since even the most sensitive periodicity searches integrate for at least 5 min, binary pulsars in orbits with $P_{\rm orb} \lesssim 1$ hour are highly selected against, as shown in Figure 2.

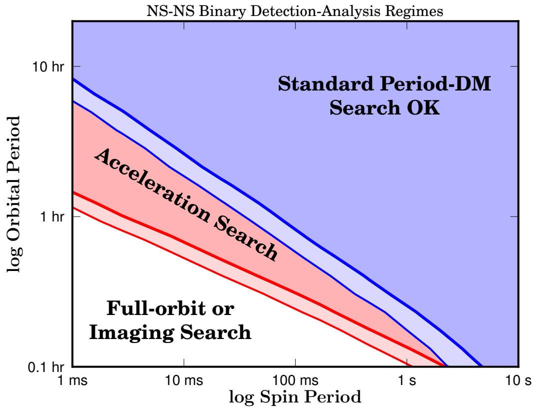

Figure 2: *Detection phase space for spin and orbital period of pulsars in NS-NS binaries.* Standard P–DM search methods are ok for large orbits and acceleration searches can handle moderate sized orbits. Sub-hour orbits require a full orbit search with more parameters, more statistical trials and high thresholds. An imaging survey can find pulsar candidates with any orbital or spin period. Contours for a more massive NS-BH binary are raised to higher $P_{\rm orb}$.

It is noteworthy that the shortest orbital period known for a binary pulsar is 93 minutes (1.5 hr), for the 2.5-millisecond black widow pulsar J1311−3430. The pulsar was detected in a gamma-ray search (Pletsch et al. 2012) and radio pulses were confirmed in a *targeted follow-up* observation (Ray et al. 2013) with the GBT, precisely tracking the proposed FS+F methodology. Further, radio emission was detected only over $<$10% of the 2 GHz discovery observation, with non-detections at both higher and lower frequencies. Ray et al. (2013) suggest scintillation, eclipses, or extreme scattering in a variable stellar wind from the Roche lobe-filling sub-stellar companion as causes for the intermittency. More typically, the double pulsar has $P_{\rm orb} \sim 2.5$ hr, and the Hulse-Taylor binary pulsar has $P_{\rm orb} \sim 7.8$ hr.

Radio Frequency Interference:

RFI is a severe problem for radio astronomy, and particularly so for time domain surveys. Sources of RFI are diverse, ranging from the prosaic and local (cellular phones, unshielded electronics and computers, power supplies) to the global (navigation satellites such as GPS and GLONASS, communication systems like Iridium, distant airport radar systems, low-flying aircraft).

Both periodicity and single pulse searches exploit the fact that pulsars experience interstellar dispersion, leading to a predictable delay signature in the pulse as a function of frequency. However, the pulse dispersion measure (DM) is a search parameter, and in the presence of RFI, candidate sources pile up at lower DMs, as illustrated in Figure 3. Since any search process will produce numerous false positives, candidates are typically ranked in order of significance and "sifted" by combining candidates at adjacent DM values and retaining only the higher significance ones. RFI compromises the candidate selection process in two ways. First, strong RFI produces candidate pulsed signals with high significance even at large DM values,

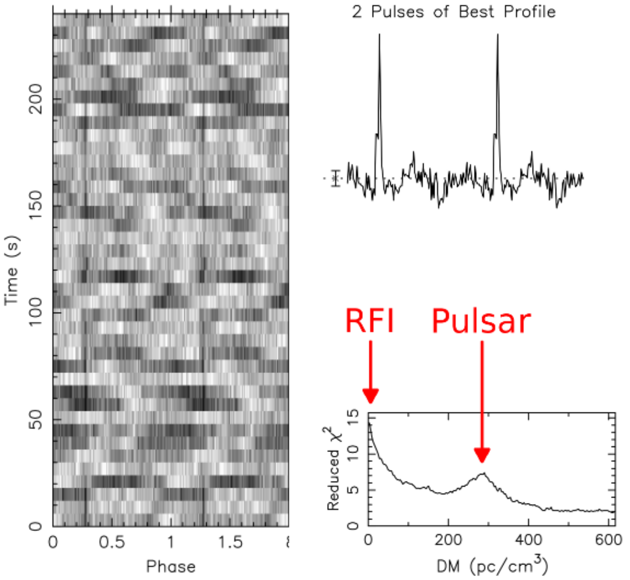

Figure 3: *Pulsar detection in the presence of RFI.* Left: the discovery data have been folded at the detected pulse period and are displayed as two cycles of pulse phase versus time. The peak of the main pulse can just be discerned between sporadic RFI bursts. Upper right: two cycles of the folded pulse profile, showing a highly significant detection. Lower right: Candidate significance as a function of trial dispersion measure (DM). Interference causes a peak in S/N ratio at zero DM, but the pulsar is detected with just enough S/N to produce a distinct peak. A weaker candidate would be swamped by the RFI and discarded.

and simply overwhelms any reasonable threshold for the number of candidates to examine. Second, a spurious RFI signal can absorb a real pulsar candidate with slightly lower significance during the sifting process. The RFI signal is subsequently rejected on inspection, but the real pulsar is lost. In Figure 3, a slightly weaker pulsar candidate at the discovery DM of ∼295 pc cm^{-3} would have been overwhelmed by RFI at neighboring DM values, and thus missed. In contrast, interferometric imaging is robust to local RFI, and contamination in the image domain is easy to identify since it appears in the form of striping or noise rather than compact source candidates.

4 Hybrid Imaging and Time-Domain Surveys for Pulsars

Targets for Hybrid Search: Along with pulsars already picked up in P–DM surveys, a hybrid survey will detect systems that are selected against in blind periodicity surveys: scattered MSPs ($P_{\rm spin} \lesssim 10$ ms) and compact binaries ($P_{\rm orb} \lesssim$ a few hours). Additionally, the survey will discover pulsars that were missed in previous searches due to pulsar intermittency and RFI.

- *Millisecond Pulsars:* Estimates give 20,000 Galactic MSPs that beam toward Earth. More than 40% of Galactic lines of sight will have $\tau_{\rm sc} > 1$ ms (see Figure 1) that exceeds MSP pulse widths and spin periods, causing them to be missed in P–DM searches. The majority of MSPs are also in binaries, some of which will be compact enough to be missed in P–DM searches.
- *Compact Binaries*: Pulsars in compact binary orbits such as the double pulsar and PSR J1311−3430 are easily detected in VLA images. Gravitational-wave induced inspiral implies that there will be binaries with $P_{\rm orb} \lesssim 10$ min with reasonable lifetimes (Allen et al. 2013). There are ∼200–2000 DNS systems in the Galaxy, likely concentrated in the inner Galactic plane, which provide laboratories for testing relativistic gravity. The few Galactic black hole-pulsar systems would provide unprecedented tests of General Relativity in a strong-gravity regime, and are likely to be at large distances with large scattering.
- *Intermittent Pulsars*: Some pulsars turn on and off on timescales that range from a single spin period to years in the case of J1841–0500 (Camilo et al. 2012), while others (like PSR J1311−3430) undergo extensive eclipses. A pulsar in the "off" or eclipsed state is undetectable regardless of survey sensitivity, motivating a multi-pass imaging survey.
- *Radio Frequency Interference*: Interferometers are more robust to RFI than single dishes, so it is likely that a hybrid survey will discover pulsars that were simply lost to RFI in P–DM searches. One such example is PSR J1906+0746, a relativistic binary that was retroactively identified within a thicket of RFI in the Parkes Multibeam Pulsar Survey data after it was discovered by the PALFA survey (Lorimer et al. 2006).

An immediate benefit of hybrid surveys is that the pulsar timing solution starts with a sub-arcsecond position. That helps bootstrap solutions for the other parameters and greatly facilitates multi-wavelength follow-up compared to pulsars discovered in single-dish P–DM surveys.

For VLA A-array observations, fits to 1.4 GHz logN-logS plots (e.g., Bondi et al. 2008; Hopkins et al. 2003) suggest source densities $\sim 10^3$ deg^{-2} above 0.1 mJy, and ~ 85 deg^{-2} above 1 mJy. With limited follow-up time and resources, a robust method is needed to prioritize pulsar candidates. Our strategy is to (1) image a field and extract sources, (2) winnow the list to select compact candidate point sources (CPS), (3) rank CPS based on criteria such as multi-wavelength counterparts, polarization, spectral index, variability, and (4) follow-up highest ranked CPS for discovery and classification. Figure 4 illustrates an application of the procedure. The 24-ms pulsar J2007+2722 was the first NS to be discovered by a globally distributed volunteer computing effort (Einstein@Home, Knispel et al. 2010, with PALFA survey data). Precise localization of the pulsar with archival VLA data allowed rapid bootstrapping of the timing solution.

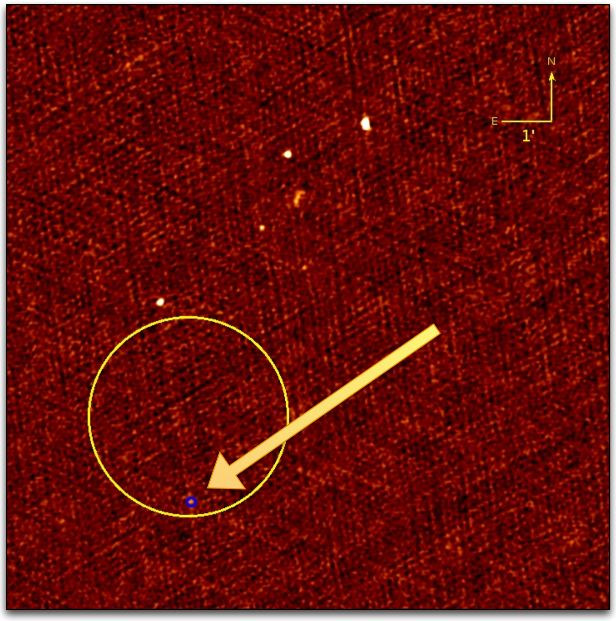

Figure 4: *An illustration of the hybrid imaging-time domain strategy.* As part of the confirmation process for the pulsar J2007+2722 (Knispel et al. 2010), we analyzed an archival VLA dataset (5 GHz, C-array) that overlapped its approximate location. 9 sources were detected, and we identified a compact source at the edge of the primary beam field of view as the pulsar counterpart. The figure shows the approximate detection position uncertainty (large yellow circle with radius $2'$) and the location of the compact counterpart (small blue circle with radius $5''$; yellow arrow). The primary-beam corrected flux density for the source is 1.2 mJy and the position is determined to $\sim 1''$ precision, enabling a phase-connected timing solution to be determined much more rapidly. An FS+F survey operates in reverse, following up only selected compact sources in the large field of view with deep time-domain observations.

Source Winnowing: The process of source winnowing is illustrated in Figure 4, and was pursued at length by Kaplan et al. (2000) for the NVSS survey. The NVSS used VLA D-array observations sensitive to extended structure; Kaplan et al. (2000) found that only 0.25% of the 30,000 NVSS sources considered passed their size and spectral index requirements.

Point Source Selection: The upper limits on the deconvolved size of an unresolved source will depend on the signal-to-noise ratio but for most sources will be $\lesssim 1''$ (Condon et al. 2012). Deep surveys with the VLA at 1.4 GHz indicate that extragalactic radio sources with $S_{1.4} \lesssim 100\mu$Jy have median sizes of $\theta_{\rm med} \sim 1\farcs2$ (Morrison et al. 2010); above 100μJy, Windhorst et al. (1990) find $\theta_{\rm med} \approx 2''(S_{1.4}/1\ {\rm mJy})^{0.3}$. Requiring sources to be unresolved at A-array/1.4 GHz will thus remove over half of the extragalactic sources without affecting pulsars. These size estimates may be unreliable (Kellerman, private communication) and subject to revision based on our initial survey results. Even pulsar wind nebulae will be mostly resolved by A-array observations, revealing the embedded pulsars.

Ranking Criteria: Compact candidates can be ranked based on multiwavelength associations, spectral index, polarization fraction, and spectral or temporal variability.

- *Multiwavelength comparison*: Counterparts can be identified in multiwavelength catalogs as in Kaplan et al. (2004). The majority of sources will be extra-galactic, with AGN dominating at fluxes $\gtrsim 1$ mJy and star-forming galaxies important below that (Condon et al. 2012; Massardi et al. 2010; de Zotti et al. 2010). Multi-wavelength (especially near-infrared) counterparts provide an efficient way to identify these galaxies. In contrast, a high-energy association in archival *Chandra* or *XMM* data (van den Berg et al. 2012) or in the *Fermi* γ-ray point source catalog increases the likelihood of being a pulsar.

- *Spectral index*: The expanded bandwidth of the VLA will allow rough estimates of the spectral index using images from each spectral window. The average pulsar spectral index ($\alpha = -1.6$) is distinct from those of most extragalactic sources ($\alpha \approx -0.7$ or $\alpha \approx 0$), but many exceptions exist.

- *Polarization*: Han & Tian (1999) found that most of the 97 bright pulsars in the NVSS had polarization fractions above 10%, while quasars and BL-Lac objects had less than 10%. We find circular polarization to be a better discriminator than linear, but will test for both; many pulsars will in fact be depolarized.

- *Spectral/Temporal Variability*: Fast interstellar scintillation (ISS) causes nearby pulsars to vary in flux across frequency and time, but ISS is quenched for distant objects in the Galactic plane. Intrinsic intermittency may also produce time variability.

Time Domain Search Observations: For selected candidates, time-domain radio data can be obtained at the GBT, Arecibo, or phased VLA. Extensive archived pulsar-search data are available from PALFA or GBNCC, but the existence and precise localization of a candidate source justifies much deeper integration (e.g., Camilo et al. 2002, 2006) and enables observation at much higher frequencies if needed to overcome scattering. A targeted search improves the statistical significance of P–DM candidates and justifies more computationally expensive orbital fitting than a blind P–DM survey.

5 Desirable and Minimal Requirements for the VLASS

The VLASS can provide the ideal finder survey for a hybrid imaging and time domain search for pulsars and transient sources. The following are the desirable and minimally acceptable criteria to enable the science goals outlined in this whitepaper.

Table 1: Suggested VLASS Survey Parameters

Parameter	**Desirable**	**Acceptable**	**Comment**
Observation Frequency	1–2 GHz	2–4 GHz	Typical $S_\nu \propto \nu^\alpha$, $\alpha \sim -1.6$
Array Configuration	A array	B at higher ν	Identify point sources.
Sky Coverage	All sky	Galactic plane + Virgo cluster	Most pulsars. Gravitational wave sources for PTAs.
Cadence	Multiple passes	2 passes	To probe intermittency.
Point Source Sensitivity	$\lesssim$100 μJy at 5σ		

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