Time Domain Radio Astronomy with the Arecibo Observatory

Laura G. Spitler[1], Julia S. Deneva[2], Chen Karako-Argaman[4], Duncan R. Lorimer[3], Ryan Lynch[4], Maura A. McLaughlin[3]

Summary

Almost fifty years ago the first time-domain radio survey discovered rapidly pulsating radio sources. These objects are now known to be radio pulsars, and their discovery launched a new, diverse branch of astrophysics. Time-domain radio astronomy is still making new discoveries. In the last decade a new class of sporadic emitting pulsars called Rotating Radio Transients (RRATs) was discovered (McLaughlin et al. 2006), and a new, so-far-unexplained class of radio bursts called Fast Radio Bursts (FRBs) have been detected (Lorimer et al. 2007; Thornton et al. 2013). Thanks to its high sensitivity and excellent complement of receivers, Arecibo is playing a key role in continuing the discoveries, primarily through two complementary pulsar surveys. As the largest radio telescope in the world, it is able to detect the faintest transients, which cannot be discovered or studied with any other telescope.

AO327 is a drift-scan survey using the 327-MHz receiver and the new PUPPI pulsar backend (Deneva et al. 2013). This survey collects data when the telescope is unscheduled (for example during maintenance or when there is a gap in the schedule) and observes largely far from the Galactic plane. The Pulsar ALFA (PALFA) survey searches for pulsars in the Galactic plane using ALFA, the seven-pixel L-band receiver (Cordes et al. 2006) and is the most sensitive survey conducted at 1.4 GHz to date. The multi-pixel receiver is key to discriminating astrophysical signals from radio frequency interference (RFI) and increasing the instantaneous field-of-view. The project involves scientists from over 20 institutions throughout North America and Europe.

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RRATs

Arecibo, being the most sensitive radio telescope in the world, is best-suited to discover the most distant and faintest RRATs. Both AO327 and PALFA have discovered many new examples (12 and 11 respectively),[1,2] which accounts for ∼20% of the total number of known RRATs. Figure 1 is an example of a newly discovered RRAT from the AO327 survey. Both surveys are also developing new algorithms that automatically identify pulses in the pipeline output. The result of this automatic classification is shown in color in Figure 1.

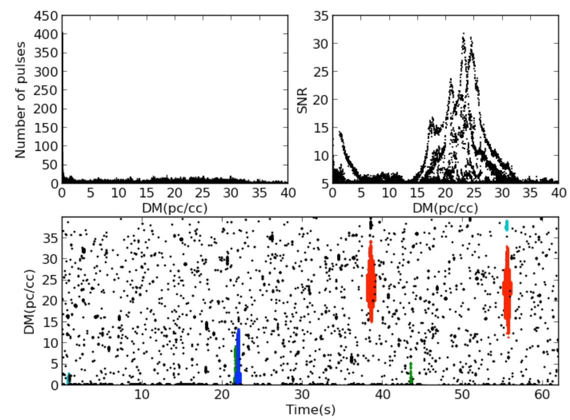

Fig. 1.— A standard single pulse diagnostic plot for an RRAT discovered in the AO327 survey. The RRAT is evident in the upper right and lower panels. The color coding in the lower panel reflects the classification determined by the automatic pulse detection algorithm. The pulses from the RRAT are colored red.

FRBs

FRBs are a new class of isolated, short-duration radio bursts observed at dispersion measures higher than expected for sources in our Galaxy, and currently there are only six published bursts (Lorimer et al. 2007; Keane et al. 2012; Thornton

[1]`http://www.naic.edu/~deneva/drift-search/`

[2]`http://www.naic.edu/~palfa/newpulsars/`

et al. 2013) (all detected at the Parkes Telescope). Although the exact nature of these bursts is still under debate, the evidence currently supports the hypothesis that they come from a population of extra-galactic objects, possibly even at cosmologically significant distances. Most of the suggested explanations involve exotic objects such as neutron stars or black holes. If they do turn out to be at cosmological distances, then FRBs will also be useful probes of the intergalactic medium.

Recently the PALFA survey discovered its first FRB (Spitler et al. 2014), which is shown in Figure 2. Arecibo is the first telescope to independently confirm the existence of FRBs, and the most believable burst at low Galactic latitudes. The FRB was detected near the Galactic anticenter, and its properties and the inferred event rate are consistent with those of the other FRBs (Thornton et al. 2013). We expect PALFA to discover several more FRBs in the future, and because it is the most sensitive telescope in the world, Arecibo has the capability to discover the most distant bursts.

Although AO327 hasn't yet discovered an FRB, it has the potential to be the first to find a burst at a frequency other than 1.4 GHz. This would be significant as it would provide a measurement of the spectra of FRBs, which would have important implications for predicting how many may be detected by next generation observatories. Also, we expect the effects of intergalactic scattering to be more significant at lower frequencies, so FRBs detected at 327 MHz would be more sensitive probes of the distribution of material along the line-of-sight.

Future Directions

One major limiting factor to discovering new transients with Arecibo is its small instantaneous field-of-view. A large field-of-view instrument such as a Phased Array Feed (e.g. "AO40") along with a realtime detection system (e.g. "ALFABURST") would be game changers. A 40-beam system with a similar sensitivity to ALFA would have ten times the sensitivity of Parkes and over five times the field-of-view of ALFA. Realtime processing pipelines are already realized at other telescopes, and Arecibo's smaller beam would make follow-up at other wavelengths easier.

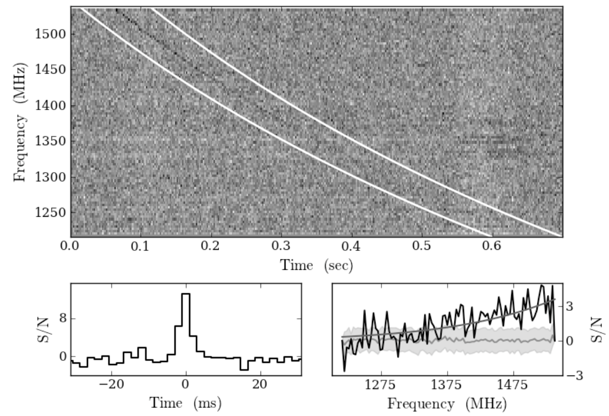

Fig. 2.— Characteristic plots for the Arecibo PALFA FRB. The dispersive frequency sweep of the burst is shown in the upper panel. The pulse profile and pulse spectrum are shown in the lower left and right panels respectively.

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Introduction to Time Domain Radio Astronomy

Time domain radio astronomy informs our understanding of astrophysics through the study of time-variable radio sources. Some of the most important astrophysical phenomena are those for which regular monitoring in the time domain is critical. For example, γ-ray bursts are the most energetic explosions in the Universe and tell us about how the most massive stars end their lives. Type Ia supernova are not only important for the study of stellar evolution, but also are a crucial tool that showed the expansion of the Universe is accelerating. Radio pulsars were first discovered when astronomers began observing the radio sky at high time resolution and are excellent laboratories for, among other things, studying extreme states of matter and testing theories of gravity.

Neutron stars are not the only astrophysical objects that are time variable. Low mass stars (brown dwarfs and M-dwarfs) are known emitters of transient radio emission (see the associated white paper for more on the transient behavior of brown dwarfs). The Sun and magnetic planets in our solar system all exhibit complex, time-variable radio emission. We also expect that exoplanets are transient radio emitters, although no emission has yet been detected. In this white paper we focus on transient sources observed as part of pulsar surveys.

The Arecibo Observatory is a world-class facility for transient science because of its high sensitivity and excellent complement of receivers. Being the most sensitive telescope in the world, Arecibo can detect transients that are weaker or more distant than any other radio telescope. For transient science, the instantaneous field-of-view is important, and although Arecibos large diameter results in a smaller field-of-view, this is not too detrimental. For example, in the case of the seven-beam ALFA receiver, the sidelobe sensitivity is comparable to the peak sensitivity of 100-m-class telescopes, which adds to the effective field-of-view. Furthermore, Arecibos receivers cover a large range of observing frequencies, which enables a wide range of complementary science. As we describe in detail below, the pulsar community is using the 327 MHz receiver and ALFA to conduct complementary surveys. The 5 GHz receiver is used by groups searching for transient radio emission from brown dwarfs (see white paper on Brown Dwarfs).

Known Sources of Transient Emission

Rotating Radio Transients

Rotating Radio Transients (RRATs) were first introduced into the pulsar literature in 2006, with the discovery of 11 neutron stars (NSs) which emitted dispersed, periodic pulses (McLaughlin et al. 2006). These NSs were not detectable, in the original search observations, through a search for periodic, or time-averaged, emission but only through their single pulses, in contrast to all of the pulsars known at the time. Since that time, all of the standard processing pipelines used in major radio surveys, including the 327-MHz Arecibo

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drift-scan search and the PALFA survey, have incorporated a search for dispersed single pulses. This has resulted in the discovery of many more objects that are only detected through their single pulses in initial survey observations (see `http://astro.phys.wvu.edu/rratalog` for a full list). These surveys, and the subsequent follow-up observations, have also demonstrated that the NS intermittency spectrum is vast and that it is very difficult to draw a firm line between RRATs and normal pulsars. Some objects that are only detectable through single pulses in initial survey observations end up being detectable through their time-averaged emission at most later epochs (and conversely, some that are detectable through time-averaged emission in initial surveys may not be in later observations!). For this reason, we believe that RRATs are a sub-class of normal radio pulsars and not a completely different category.

Despite this, the discovery and subsequent follow-up of these types of pulsars is important for several reasons. First, measuring their properties allows us to determine the selection effects against their discovery and, in turn, the total population of these objects. Given their sporadicity, they imply a much higher number of NSs, which could even lead to inconsistencies with Galactic supernova rate estimates! Second, understanding the reasons for their sporadic emission is important for understanding the pulsar emission mechanism in general. Is their unusual emission due to intrinsic or extrinsic factors? Is there some correlation between the emission properties and spin-down properties? Third, observations of one RRAT revealed unusual X-ray properties, including spectral absorption lines and a very bright nebula (McLaughlin et al. 2007). It remains unclear whether these properties are somehow related to its unusual X-ray emission.

The Arecibo Observatory is the most well-suited telescope in the world to answer these questions. As longer integrations offer no improvement to the sensitivity to these sources, access to a large telescope is critical. In fact, some of the RRATs discovered with Arecibo could never be observed with any other telescope in the world! In order to address the issues in the previous paragraph, a sustained searching and timing program with Arecibo is necessary. Of the nearly 100 RRATs currently known, only 20% have timing solutions due to the sporadicity of their pulses. However, while achieving timing solutions can take some time, the payoff is well worth the investment as there is no other way to measure the physical properties of RRATs and thus make progress towards understanding their behavior.

Fast Radio Bursts

Fast Radio Bursts (FRBs) are a new class of short-duration radio bursts first discovered in archival pulsar search data from the Parkes Telescope in Australia (Lorimer et al. 2007). The bursts are broadband, have flux densities on the order of 0.1 Jy, and have durations of $\sim$1-10 ms. Since the initial detection, one candidate FRB has been reported from the inner Galaxy (Keane et al. 2012) and four FRBs have been detected far out of the Galactic plane (Thornton et al. 2013).

They distinguish themselves from other short-duration radio pulses (i.e. single pulses from RRATs) in two ways. Firstly, the measured dispersion measure (DM, the column density of free electrons towards the source) is much larger than the DM predicted by the NE2001 model (Cordes & Lazio 2002), the standard model of Galactic electron distribution, for the burst's line-of-sight. In the case of the four Thornton et al. (2013) bursts, the expected Galactic contribution is only 3-6% of the total observed DM. This suggests that the source of FRBs is in fact extragalactic with the extra observed DM coming from a possible host Galaxy and intergalactic medium. Thornton et al. (2013) extrapolated an event rate of FRBs from their four bursts of $1.0^{+0.6}_{-0.5} \times 10^4$ bursts sky^{-1} day^{-1}. The second defining characteristic of FRBs is the absence of repeated bursts. The observed sky positions of FRBs have been followed up with additional observing, and to date, no additional pulses have ever been seen.

The astrophysical source of FRBs is currently under debate, and much like the situation shortly after the discovery of GRBs, there are more theories than bursts. Several theories suggest extragalactic, destructive origins including merging NSs (Hansen & Lyutikov 2001) or the collapse of supramassive NSs (Falcke & Rezzolla 2014). Alternatively, FRBs could be extremely bright, exceedingly rare instances of known short-duration bursts such as pulsar giant pulses or magnetar flares (Popov & Postnov 2007). Clearing up this situation will require rapid follow-up with telescopes at other wavelengths.

Although the origin of FRBs is currently unknown, we do know that they are telling us something new about high-energy physics. Additionally, they may also prove to be useful cosmological probes. One can make a rough estimate of the distance to the FRB using the observed DM excess. For the currently published bursts, this yields redshifts of $z \approx 0.3$-3. As cosmological probes, FRBs have many uses. Measuring interstellar scattering effects in FRBs will give us insight into the turbulence of the intergalactic medium (Macquart & Koay 2013). Once we have a large sample of FRBs, the distribution of observed DMs can tell us how baryons are distributed outside the virial radius of Galaxies, which is important for solving the "missing baryon problem (McQuinn 2014). A key step in advancing FRB science is an independent distance estimate from a counterpart at another wavelength, which would also allow models of the IGM to be tested and better calibrated.

Arecibo Pulsar Surveys

Arecibo 327 MHz survey

The Arecibo 327-MHz survey (AO327) is a drift-scan survey of the portion of the sky accessible to the Arecibo telescope (DEC = -1 to 38 deg) and collects data at times when the telescope is parked for maintenance or repairs (Deneva et al. 2013). Up to early 2014, data were taken with the Mock spectrometer over a 57 MHz bandwidth. Since February 2014, data are taken with the newer PUPPI backend over a 68 MHz bandwidth with superior time and frequency resolution. The low observing frequency means that the survey is not sensitive to high-DM sources near the Galactic plane, but the steep spectra of pulsars makes this survey the most sensitive in the world for RRATs out of the Galactic plane. It could also be the most sensitive FRB survey if their spectra are similar to pulsars. This survey is currently being searched for pulsars and transients out to DMs of 1000. Past this DM, we would expect scattering to prohibit the detection of any short timescale phenomena.

To date, AO327 has found 44 pulsars, including 12 RRATs[1]. Eleven of the RRATs were identified by a single-pulse candidate ranking algorithm designed to automatically distinguish dispersed, celestial pulses from terrestrial radio frequency interference (RFI) (see Figure 1). One of the RRATs has a DM of 133 pc cm^{-3}, making it the highest-DM discovery for the drift survey. Single pulses from known pulsars at DMs as high as 240 pc cm^{-3} have been detected as well.

Although no FRB has yet been detected in the AO327 survey, estimates assuming the previously published event rate suggest that AO327 has roughly the required amount of time on the sky to detect one. This estimate is highly uncertain as no FRB has been seen at a frequency other than 1.4 GHz, but such a detection would be extremely important for elucidating the nature of FRBs across a wide range of frequencies. Furthermore, we expect a burst at a lower observing frequency to be more strongly affected by intergalactic scattering, but how strongly they are affected is one of the biggest unknowns in the study of FRBs. Therefore, the discovery of a burst from AO327 would be extremely exciting.

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[1] `http://www.naic.edu/~deneva/drift-search/`

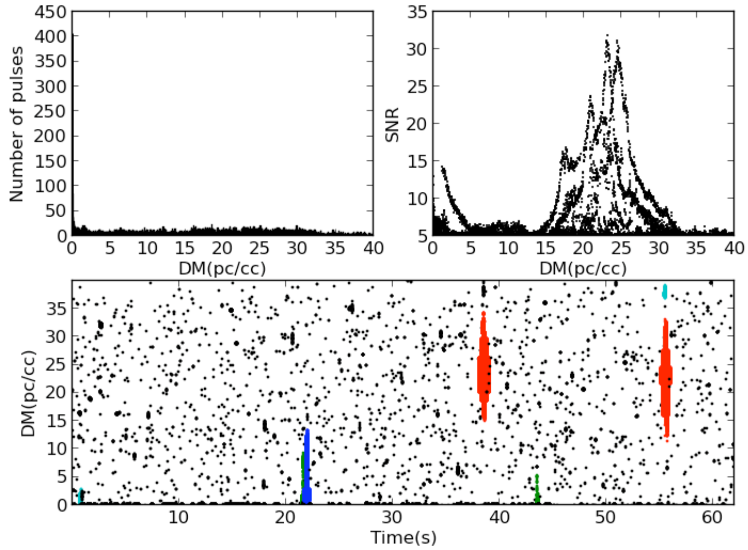

Fig. 1.— A standard single-pulse diagnostic plot for a new RRAT discovered in the AO327 survey. The RRAT is evident in the upper right and lower panels. The color coding in the lower panel reflects the classification determined by the automatic pulse detection algorithm. The RRAT pulses are colored red.

Pulsar ALFA survey

The Pulsar ALFA (PALFA) survey is a blind survey for pulsars concentrated in the Galactic plane and is the most sensitive pulsar survey conducted at 1.4 GHz to date (Cordes et al. 2006). Data are collected with the seven-pixel ALFA receiver and the Mock spectrometers. The survey is divided into the two regions of the Galactic plane visible in the Arecibo sky: inner Galaxy and outer Galaxy. Since it began in 2004, PALFA has discovered 135 new pulsars, of which eleven are RRATs, and one FRB Spitler et al. (2014) (recently accepted for publication in ApJ).

The transient processing has become an important component of the PALFA survey processing. Not only does it enable us to find sporadic emitters such as RRATs and, recently, an FRB, but it is also an important tool in combating RFI. Recent sensitivity studies of PALFA data suggest that the periodicity search algorithms are less sensitive than expected for long-period pulsars because of RFI. Because RFI affects transient searches differently, the single-pulse processing has caught pulsars that were missed because of RFI but are clearly visible as periodic sources using the properties determined from the single-pulse algorithms. Also, PALFA is developing new algorithms to automatically identify real, astrophysical pulses in the pipelines single-pulse output, a process which was previously done manually.

The new FRB discovered by PALFA is the first one seen by a telescope other than Parkes. The burst was observed at a low Galactic latitude in the outer Galaxy. The observed DM of this burst was 557.4 pc cm^{-3}, where the predicted DM from this line-of-sight is only 188 pc cm^{-3} (See Figure 2). This DM excess puts the burst at a redshift of up to z=0.25. The other observational properties of the burst (e.g. pulse duration, flux density) are all consistent with the properties of the Thornton et al. (2013) bursts. Finally, given the event rate published by Thornton et al. (2013) and the amount of PALFA data analyzed, it is expected that we would have found one burst.

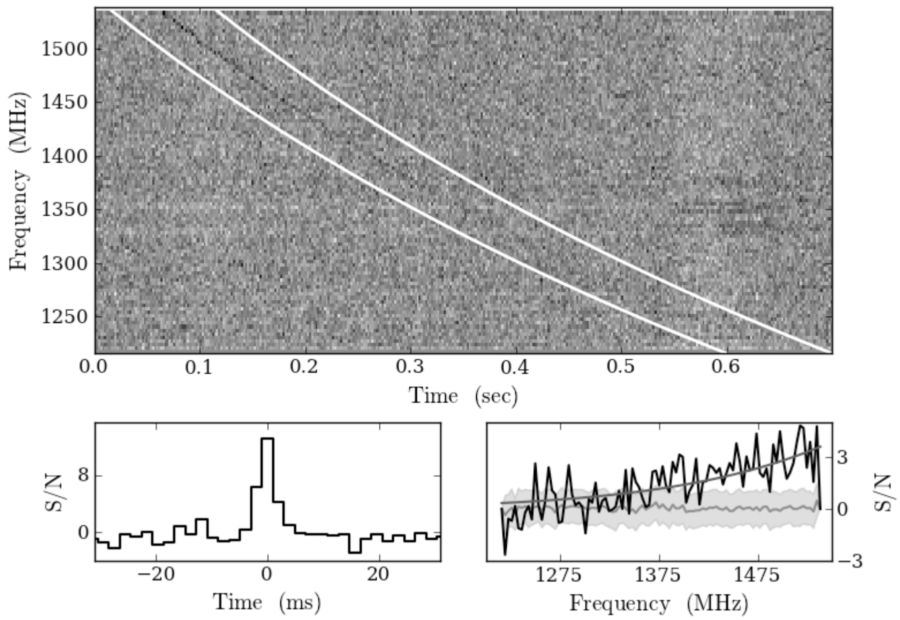

Fig. 2.— Characteristic plots for the Arecibo PALFA FRB. The dispersive frequency sweep of the burst is shown in the upper panel. The pulse profile and pulse spectrum are shown in the lower left and right panels respectively.

Future Directions

One major limiting factor to discovering new transients with Arecibo is its small instantaneous field-of-view. A large field-of-view instrument such as a Phased Array Feed (e.g. "AO40") along with a realtime detection system (e.g. "ALFABURST") would be game changers. A 40-beam system with a similar sensitivity to ALFA would have ten times the sensitivity of Parkes and over five times of the field-of-view of ALFA. Realtime processing pipelines are already realized at other telescopes, and Arecibo's smaller beam would make follow-up at other wavelengths easier.

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