Pulsar Searching with the Arecibo Radio Telescope

Pulsars, rapidly spinning highly magnetized neutron stars, have long been known as excellent tools to study fundamental physics and astronomy. They have so far been used as tools to investigate a wide variety of topics, including exotic matter physics, low-frequency gravitational waves, fundamental tests of general relativity, interstellar weather, globular cluster astrophysics, extrasolar planets, and planetary physics. Of particular interest are "millisecond pulsars" (MSPs) which rotate with frequencies up to several hundred Hz with clock-like precision. Recent surveys have been extremely successful in revealing the population of MSPs both in our Galaxy and in its globular cluster system. In the light of these discoveries, it is certain that many pulsars and transients, some with exotic properties, remain to be found in the coming decade. These new objects will provide transformational science. The 305-m telescope at the Arecibo Observatory (AO) has played a key role in many of the discoveries so far. About 25% of all MSPs currently known in the Galactic disk have been found at AO. The telescope has significant discovery potential for the rest of this decade and beyond.

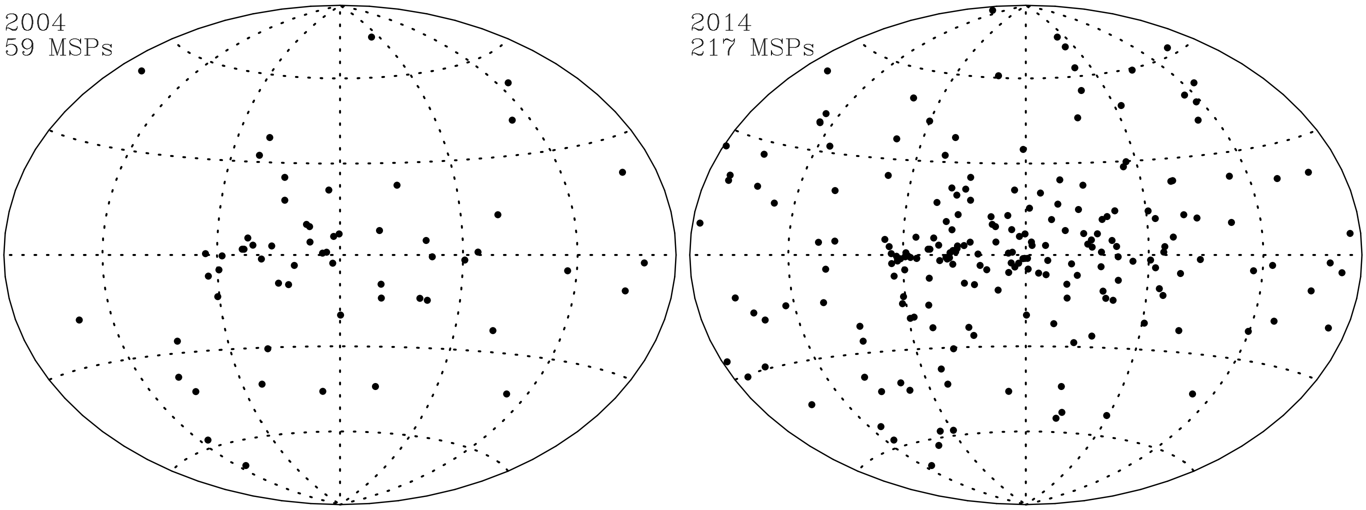

Figure 1: *Sky distributions in Galactic coordinates showing Galactic disk MSPs a decade ago (left) and today (right) which reveal the dramatic increase in the sample size due to more sensitive searches. An up-to-date list of MSPs can be found at http://astro.phys.wvu.edu/GalacticMSPs.*

Key science goals for finding more MSPs

The currently known pulsars represent only a tiny fraction, on the order of 0.1%, of the Galactic neutron star population. Finding as many pulsars as possible is important for many astrophysical applications. In addition to building up a complete picture of the birth and evolution of pulsars, pulsars probe the interstellar medium and the Galactic magnetic field. On a more fundamental level, the three main areas outlined below can only be addressed by finding and studying more pulsars.

Goal #1: Make fundamental advances in gravitational physics
Ever since the landmark discovery of the first double neutron star system (Hulse & Taylor 1974), high-precision timing observations of binary pulsars have enabled a variety of tests of relativistic theories of gravity. Pulsars with stellar-mass black hole companions, and orbiting the supermassive black hole at the Galactic center (Sgr A*) are expected to be found soon and will significantly advance this area of fundamental physics via precision measurements of relativistic observables.

Goal #2: Probe the equation of state of matter at high densities
Neutron stars are excellent probes of the physics of matter at the highest densities. High mass

and/or extremely rapidly rotating neutron stars have so far allowed us to rule out a number of the many proposed equations of state. Further progress will be made in the future with the discovery of other outlying (in spin or mass) systems or of a pulsar for which both the mass and radius can be measured. Such a measurement may be possible for the double pulsar system within five years.

Goal #3: Study the Universe via low-frequency gravitational waves
The direct detection of gravitational waves remains one of the greatest challenges confronting modern experimental physics. As described in a separate document, currently a large consortium of astronomers in North America (aka NANOGrav) monitors a network of pulsars using the Green Bank Telescope and AO to search for gravitational-wave induced correlated changes in pulse arrival times. The technique is sensitive to low-frequency (nanohertz) waves produced by coalescing supermassive black holes at the centers of distant galaxies, as well as individual continuous or transient sources of gravitational waves including known and unknown populations. Crucial to the sensitivity of the array is the number of pulsars included. The large number of millisecond pulsars now being discovered is therefore contributing directly to the ultimate success of this effort.

Ongoing projects with Arecibo

The Pulsar Arecibo L-band feed array (PALFA) survey is observing the Arecibo-visible portion of the Northern Galactic Plane using the 7-beam Arecibo L-Band (1.4 GHz) feed array. An international consortium of over 30 astronomers from half a dozen countries is carrying out this survey with the primary goal of detecting millisecond pulsars in far larger volumes of the Galaxy than has previously been possible. Only 30% of the survey region has been observed and processed but already 135 pulsars have been discovered, including 14 millisecond pulsars, one relativistic binary, the first eccentric millisecond pulsar binary known in the Galactic disk, and 11 rotating radio transients (RRATs). Very recently, the discovery of a fast radio burst with PALFA was also announced. These sources are described in detail in a separate document, and underscore the importance of pulsar surveys as discovery machines for transient science.

The Arecibo 327-MHz drift scan survey takes advantage of times when AO is unavailable for routine observations and collects search-mode data at 327 MHz as the sky drifts overhead. So far, a total of 44 discoveries have been made, including 4 MSPs, one relativistic binary and 12 RRATs. Dozens of further discoveries are expected over the coming 1–3 years.

Globular cluster surveys exploit the huge stellar densities in globular clusters which increase the stellar interaction rate, making them virtual factories for MSPs. Searches of globular clusters with AO have uncovered around 20% of all 150 cluster pulsars currently known. The stellar interactions also produce exotic MSP binaries which would be exceedingly rare in the Galactic disk. Examples of such strange and scientifically interesting systems include MSP—main sequence star binaries which can be observed in other wavebands, highly eccentric binaries where relativistic effects allow us to measure MSP masses, and the fastest known rotating neutron star (at 716 Hz!) which constrains the equation of state of dense matter.

Fermi-Directed Pulsar Surveys have, in the last five years, exploited a unique synergy with NASA's Fermi Gamma-ray Space Telescope with spectacular results. The Fermi Large Area Telescope has discovered and characterized many hundreds of gamma-ray sources that have spectra and variability properties like the known gamma-ray pulsars but without any known counterparts. Using telescopes around the world, the Fermi Pulsar Search Consortium has been searching these sources for radio pulsars. This is feasible because the LAT localizations are good enough to perform a deep search in a single pointing. These searches have been incredibly efficient at discovering new MSPs, with 64 discoveries so far. Searches with AO have discovered 6 of these within the past 12 months, and many more are expected over the coming year.

Future developments

While all of the above projects continue to be very successful, they are ultimately *sensitivity* limited. Currently, around 1/10 of MSPs have the necessary timing precision and stability to make a strong contribution to pulsar timing arrays. Recent studies suggest that around 100 MSPs are needed in such arrays to study gravitational waves in significant detail beyond the initial detection. To increase the known MSP population to around 1000 will require substantial new investments in instrumentation and facilities. In the subsections below, we outline the requirements pertinent to searches at AO.

Phased array feeds

It is imperative that AO be outfitted with instruments that will enable us to further the science goals we have outlined above. To advance pulsar surveys at AO, a wide-field system is needed to improve throughput and sensitivity over that of the seven-beam ALFA system. A state-of-the-art approach is a cooled phased-array feed system. A prototype system has been developed which could ultimately lead to a 40-beam system ("AO40"; see below) with the same sensitivity as a conventional feed-horn system. Building this requires innovations such as a large dewar window and high-rate signal processing for the digital beam forming, both of which are on their way to being achieved. A successful system will be a major milestone in instrumentation development as, to date, no phased-array feed system has been used for a large-scale research project. It will enable AO surveys to find a further 1000 pulsars.

Data acquisition systems

Only in the last five years have pulsar data acquisition systems had enough capability (in terms of bandwidth, sampling rate, and number of channels needed to combat interstellar dispersion) such that we are fully as sensitive to MSPs as a simple radiometer equation analysis suggests we should be. Furthermore, previous surveys missed many MSPs simply because of a lack of computing and signal-processing power. Currently planned multi-pixel systems and phased-array feeds will demand state-of-the-art pulsar "backends" for *each* pixel on the sky, each producing data at 50–100 MB/s. The next decade will require the development of new capabilities to handle and process such prodigious amounts of data. Much of the success in backend development has been due to the NSF supported Center for Astronomy and Signal Processing Research (CASPER) project at Berkeley. In particular, staff at NRAO have worked closely with the CASPER team to develop backends for AO.

Data archiving

The high time and frequency resolution necessary to detect pulsars in radio telescope data means that the raw data themselves are extremely voluminous. Modern surveys routinely produce hundreds of TB of data. New, improved algorithms for detecting faint signals, particularly in the presence of strong interfering signals, are constantly being developed. Moreover multi-wavelength discoveries of pulsars, e.g. using Fermi or in the X-ray band, often motivate re-analyses of radio search data in search of a known periodicity. For these reasons, data archiving is very important for radio pulsar search data, in order to keep a long-term copy of these scientifically valuable and unique data sets. We strongly advocate for more consideration of this problem, as data archiving is now routinely done in nearly all other branches of astronomy.

Potential for non-NSF funding

Over the past five years, pulsar searching activities using NSF facilities have greatly benefited from external resources made possible by the open-skies policy at AO. All of these have enabled a significant number of additional pulsar discoveries. Within the PALFA consortium, for example, significant advances have been made through cyber infrastructure funded by the Canadian CANARIE institute. The sophisticated facilities for the selection and tracking of pulsar candidates within this architecture are now being adopted for other surveys as well (this is in addition to a substantial investment in archival storage and data processing already provided by Canadian and European colleagues). Non-U.S. funding is currently being sought to fund three FTE scientists at AO with Canadian participation. Additional contributions include Canadian development of data acquisition systems (UBC) and German contributions to processing resources (MPI Hannover). Canada's stated strategic priority of developing information and communications technology has the potential for new funding to develop pulsar search data management and visualization. In addition to these opportunities overseas, we continue to explore funding via private foundations (e.g. The Research Corporation for Scientific Advancement, the Moore Foundation and the Keck Foundation), state programs (e.g. EPSCoR) and other federal initiatives (e.g. DOD).

Outreach opportunities

Following the very successful pulsar search program involving the analysis of Green Bank Telescope by high-school students[1], part of the AO-327 MHz drift-scan survey data is being set aside exclusively for the analysis by undergraduate students at West Virginia University. A similar program targeted at high-school students and undergraduates is the Arecibo Remote Control Center (ARCC) at the University of Texas at Brownsville, and the University of Wisconsin Milwaukee. In addition, using the Einstein@Home network to distribute data, PALFA is also responsible for the first pulsar discovered by global volunteer computing. These activities have broadened participation and interest in pulsar searching over the past several years, and we expect this trend to accelerate as the volume of data to be mined continues to grow. These programs have been incredibly successful at increasing the enrollment of minority groups into careers in STEM disciplines, especially Physics and Astronomy.

Undergraduate and graduate training

The number of graduate students working on pulsar-related projects in the U.S. is currently at an all-time high. Many of these students will go on to postdoc and faculty positions to help sustain the next generation of neutron star astronomers. Thanks to the development of CASPER, many current students are obtaining training in digital signal processing development. This is crucial to the success of all next generation instruments and the long-term future of this field. Finally, we note that pulsar researchers have a long track record of developing extensive data management, supercomputing, and data visualization skills that are applicable to a wide variety of disciplines both within and outside the physical sciences.

[1] This is an NSF-ITEST-funded outreach project based in West Virginia known as the Pulsar Search Collaboratory (http://pulsarsearchcollaboratory.com). Since 2008, involved over 1800 high-school students and 100 teachers in 18 U.S. states. This collaboration has so far found six pulsars, including one MSP.