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Arecibo and the Pulsar Census: Gravity, the Equation of State and Galactic Structure

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Why Arecibo is Important for Pulsar Science

Pulsars continue to provide unique opportunities for pushing frontiers in astrophysics and testing gravity. Arecibo has had and will continue to have a crucial role in realizing these opportunities. A comprehensive Galactic census of neutron stars is the eventual target of the Square Kilometer Array (SKA) project. It will build upon work that can be done with Arecibo and other telescopes *now.* The census, of course, is just the starting point. It yields discoveries of objects that are best suited for diagnosing theories of gravity, for detecting nano-Hertz gravitational waves, and for constraining the nuclear equation of state (EoS), all through precision timing observations over time spans of five years or more.

Arecibo's role in the study of neutron stars will remain unique until the Chinese FAST[1] telescope comes on line some time in the next decade and until SKA reaches comparable capability. Arecibo's prominence will be in the following areas:

I. Deep searches for pulsars. Arecibo surveys with ALFA[2] have minimal bias against the most fastly spinning millisecond pulsars (MSPs) and pulsars in very compact binaries.

The high time and frequency resolution of the back-ends employed in the ALFA pulsar surveys allows the detection of MSPs at very high Dispersion Measures (DMs). A great example of this is the recent discovery of PSR J1903+0327, a 2.15-ms pulsar at a record high DM (for an MSP) of 297 pc cm^{-3}. This means we can search unprecedented volumes of the Galaxy for MSPs, particularly for objects faster than 1 ms. MSPs with high timing precision can be used as detectors of cosmological gravitational waves at nHz frequencies; MSPs spinning faster than 1.5 ms, possibly as fast as 0.5 ms, probe the equation-of-state under the extreme conditions found inside neutron stars (NSs); they can also be emitting significant amounts of gravitational waves. LIGO is very sensitive precisely at the frequency range occupied by these fast-spinning pulsars.

The high gain of the telescope gives the ALFA pulsar surveys unprecedented sensitivity with integrations that are only 4.5 minutes long. This means that we retain sensitivity to highly accelerated binary pulsars, as demonstrated by the discovery of PSR J1906+0746 (Lorimer et al. 2006), the second-most relativistic binary known and the youngest binary pulsar known.

The *combination* of high sensitivity and high time-frequency resolution is perhaps the most important factor in determining the scientific outcome of these surveys. It gives us truly unique sensitivity to fast-spinning pulsars in tight binary systems. Binary pulsars with relativistic companions, including black holes, can be used to test GR and, more generally, the principle of equivalence and other fundamental properties of gravitation and space-time.

II. Timing Precision. Using pulsars as clocks is the key to achieving the key science that is the subject of this document. Millisecond pulsars are the best pulsar clocks and the goal by the broad community is to improve timing precision to well below the 0.1 μs level on a few dozen objects in order to detect gravitational wave backgrounds. For the brighter MSPs, signal-to-noise ratio is secondary to other effects (such as intrinsic spin or orbital noise and propagation effects from the interstellar medium) in clock precision. Arecibo can be used to make timing observations at higher frequencies — where MSPs are dimmer — as a means for minimizing some of the plasma propagation effects. Arecibo can also play a key role in diagnosing systematic errors. For this, signal-to-noise is most likely crucial and Arecibo is therefore the ideal testbed for realizing the ultimate timing precision in advance of the SKA, where these systematic errors (not lack of signal-to-noise) will be dominant.

III. High-Sensitivity Astrometry. As the world's largest aperture, Arecibo plays a critical role in the High Sensitivity Array, a global array of the largest antennas operating as a very-long-baseline network that provides sub-milliarcsecond angular resolution. HSA observations of pulsars provide highly valuable proper motion and parallax measurements that are crucial for pulsar timing models, for understanding natal momentum kicks

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[1] The Five-hundred-meter Aperture Spherical Telescope. though formally larger than Arecibo, only about 300m will actually be used at any time. Also, the frequency range may not extend as high as Arecibo.

[2] Arecibo L-band Feed Array, a 7-beam system currently used for multiple surveys, including a large-scale pulsar survey

imparted to neutron stars in core-collapse supernovae, and for providing anchor points in Galactic models of electron density and magnetic field.

The Galactic Pulsar Census

Radio pulsars continue to provide unique opportunities for testing theories of gravity and probing states of matter otherwise inaccessible to experimental science. In large samples, they also allow detailed modeling of the magnetoionic components of the interstellar medium (ISM). For these reasons the worldwide pulsar community has recognized that a Galactic census of radio pulsar is a long term goal that will be realized in its final stages with the Square Kilometer Array. The Arecibo telescope is essentially a 10% SKA in terms of its pulsar sensitivity and it can be used to great profit in reaching many of the goals that are part of the SKA science case.

The benefits of a complete Galactic census are obvious. In addition to finding objects that can be used to test gravitational theories, to detect nano-hertz gravitational waves, and to study extreme conditions inside neutron stars, these include:

- The high sensitivity of Arecibo allows detection of intermittent pulsars, a population that has been biased against in most prior surveys, and that recently has been shown to contain members of great astrophysical interest.
- Hypervelocity pulsars with translational speeds in excess of 10^3 km s^{-1}, which constrain both core-collapse physics and the gravitational potential of the Milky Way;
- Objects with unusual spin properties, such as those showing discontinuities ("glitches") and apparent precessional motions (including 'free" precession in isolated pulsars and binary pulsars showing geodetic precession); and
- Radio pulsars with magnetic fields so high that their rotational properties makes them similar to magnetars, illuminating the similarities and differences between radio pulsars and magnetars.

The second reason for a full Galactic census is that the large number of pulsars can be used to delineate the advanced stages of stellar evolution that lead to supernovae and compact objects. In particular, with a large sample we can determine the branching ratios for the formation of canonical pulsars and magnetars. We can also estimate the effective birth rates for MSPs and for those binary pulsars that are likely to coalesce on time scales short enough to be of interest as sources of periodic, chirped gravitational waves (e.g. Burgay et al. 2003).

The third reason is that the large pulsar sample can be used to probe and map the ISM at an unprecedented level of detail. With various measures (DM, RM, SM, etc.) on a large number of directions, much more detailed maps can be constructed of the Galaxy's gaseous and magnetic components, including their fluctuations.

Accomplishing pulsar science involves observational activities in items I, II and III cited above, all of which require the high point-source sensitivity that Arecibo can provide.

The Numbers

Canonical pulsars — those with magnetic fields of $10^{12\pm1}$ G — are born at a rate $\sim 1/100\,\mathrm{yr}$ and typically survive as radio emitters for 10 Myr. This yields $\sim 10^5$ active pulsars in the Galaxy of which a fraction $f_b \sim 0.2$ beam toward us, or $\sim 2\times10^4$ detectable pulsars. Roughly half the canonical pulsars will escape the Galaxy owing to their large velocities.

Millisecond pulsars (P$\lesssim$ 20 ms and surface fields $\lesssim 10^9$ G) have a birth rate about 100 times smaller than that of canonical pulsars but emit radio waves for at least 100 times longer. Thus the MSP population is comparable in size to the canonical pulsar population. Their velocities are smaller so they are a bound population with a scale height ~ 0.5 kpc.

Relativistic binary NSs merge at a rate $\sim 10^{-5.5} - 10^{-3.7}$ yr^{-1} (3 to 190 per Myr, Kim et al. 2006, astro-ph/0608280) and have a birth rate somewhat larger, as some will not merge on a Hubble time. Mergers occur on time scales $\sim 50 - 200$ Myr, typically, so the number of NS-NS binaries in the Galaxy $\sim 50 - 10^{4.6}$ and the number beamed toward us $\sim 10 - 10^{3.9}$.

High field pulsars and magnetars: radio pulsars with fields $\gtrsim 10^{13}$ G and magnetars found in X-ray surveys now appear empirically less distinct, especially since two magnetars have been found to emit strong radio pulses, albeit with flat spectra that extend to distinctly non-traditional frequences of 100 GHz or higher. Magnetars are few in the Galaxy, but perhaps more are to be found as they burst at radio wavelengths.

Intermittent pulsars: Rotating radio transients ("RRATs") and long-nulling pulsars have emerged as empirical classes in just the last two years. They are important for two reasons. First, as part of the overall census, it is not clear to what extent pulsars have been undercounted in survey analyses. Second, these objects provide new, critical information about relativistic magnetospheres, including the fact that in the burst state, objects like B1931+24 (Kramer et al. 2006 Science, 312, 549) show a larger torque (higher $\dot{P}$), indicating that the relativistic particle flow is itself modulated. Given the relative insensitivity, until recently, of pulsar surveys to intermittent objects, it is almost certain that new objects will be found, perhaps in new physical as well as empirical classes.

A Pulsar Roadmap for the Next Decade

The science themes are essentially already identified and will require at least a decade to be fulfilled: testing gravity, gravitational-wave detection, the equation of state of NS, relativistic magnetospheres and acceleration processes, and the magneotionic structure of the Milky Way. These themes require courses of action on several fronts.

ALFA Pulsar Surveys: Over the next 5 years at least, and arguably the next decade, the main pulsar surveys at Arecibo will continue to use the ALFA system. The current survey is only of the Galactic disk (within five degrees of the midplane). Out-of-plane surveys, extending to ~ 30 deg latitude, say, will optimize detection of MSPs and relativistic binaries. Intermittency demands that surveys be repeated, perhaps episodically.

ALFA has already found important objects in all the key categories, including a relativistic binary pulsar in a 3.98 hr orbit (PSR J1906+0746, mentioned above); an enigmatic MSP (PSR J1903+0328), which is also the first MSP in the Galaxy known to have an eccentric ($e = 0.44$) orbit; an object almost certain to be detectable with GLAST and which has an unusually flat radio spectrum (PSR J1928+1746); and intermittent pulsars that have been biased against in most previous surveys.

Timing Observations: In total, hundreds and perhaps one thousand pulsars will be found in ALFA surveys over the next decade. Timing observations with Arecibo will be needed into the indefinite future in order to reap the benefits of survey discoveries in testing GR, using binary pulsars to measure post-Newtonian effects that allow estimation of individual NS masses, and to detect nHz gravitational waves as part of the pulsar timing array enterprise.

VLBI Astrometry: Pulsar parallaxes are difficult to measure owing to the faintness of the targets and especially to ionospheric perturbations at frequencies where pulsars are strong. Nonetheless, with the VLBA only, the largest parallax distance so far is 2.4 kpc (Chatterjee et al. 2005, Ap J Letters, 630, 61). With Arecibo as part of the high-sensitivity array (HSA), a much larger sample size can be targeted and higher-frequency observations can be used for some objects, thus mitigating much of the ionosphere's effects.

ALFA and Beyond: While ALFA surveys are compelling for many years in the future, along with related timing and astrometry observations at a range of frequencies, other programs can also be contemplated that require the use of Arecibo, as we now describe.

Low-frequency surveys: Venturing to frequencies lower than ALFA's 1.4 GHz band is certain to yield discoveries of steep-spectrum objects, such as MSPs. There is significant search phase-space that cannot be reached with the GBT, namely dim pulsars in very compact binaries. The sweet spot is probably between 0.5 and 1 GHz, a particular choice requiring consideration of RFI.

Another opportunity arises from the yields expected from low-frequency array projects operating in the 30 to 200 MHz bands (LOFAR, LWA, and MWA). While these telescopes will find some nearby pulsars as pulsed objects, many sources will be seen in imaging surveys as steady sources because pulses will be smeared out by scattering. Objects identified in imaging surveys that otherwise have pulsar-like characteristics (spectral index and polarization, for example) can be confirmed with Arecibo at high-enough frequencies that pulse smearing is not an issue.

Joint Gamma-ray and Radio Observations of Pulsars: AGILE (Astro-revelatore Gamma a Immagini L'Eggero) and the Gamma-ray Large Area Space Telescope (GLAST) will revolutionize our ability to study the gamma-ray sky, primarily owing to the high sensitivity combined with better angular resolution. GLAST will survey the entire sky every three hours and will find pulsars in blind surveys as well as in targeted observations that make use of radio-determined timing ephemerides. Fundamental issues in our understanding of rotation-driven pulsars and transient sources will be addressed through carefully defined radio observations that complement GLAST. These include (1) studies of pulse profiles for understanding the relative orientation of the radio and gamma-ray beams;

high-quality radio polarization profiles from Arecibo can define orientation angles of the radio beam and magnetic axis, providing crucial information for the joint study; (2) simultaneous radio and gamma-ray observations that target understanding of intensity modulations in both bands in terms of magnetospheric models and relativistic flows; (3) understanding acceleration gap regions in pulsar magnetospheres; and (4) understanding the empirical radio and gamma-ray selected source populations and the degree to which one is radio quiet and the other gamma-ray quiet.

In these endeavors, Arecibo can play a crucial role in providing precise timing of weak pulsars that will enable detection by GLAST. Arecibo also will find young, high-$\dot{E}$ objects that will be good targets for GLAST. The current ALFA survey has in fact already found such a pulsar within an error box of an unidentified EGRET source. This pulsar (J1928+1746) is on the "must-do" list of pulsars to be analyzed with GLAST. For objects discovered with GLAST (either as pulsed sources or as point sources with too few photons to identify pulsations), Arecibo will be used to search for radio pulsations at the gamma-ray position, which now will be sufficiently accurate to be sampled with a single-beam system at Arecibo. Finally, as mentioned, full-Stokes pulse profiles are highly valuable for understanding radio and gamma-ray beaming from pulsars. Arecibo has already provided many such profiles and, for new discoveries, will continue to do so.

Study of Matter at High Densities: The discovery of the first millisecond pulsar (MSP), PSR B1937+21, in 1982, also at Arecibo, has put important constraints on the size and mass of neutron stars: if their radii were larger than 20 km they would fly apart under such a fast rotation. These constraints are important in the study of the equation of state (EOS) for cold matter near the quark de-confinement regime. Such a region of the temperature-density plane cannot be reached in any known laboratory experiments, which can only probe the properties of matter at much higher temperatures and much lower densities. Finding an MSP with a spin frequency larger than 1,000 Hz would eliminate some of the "hard" (higher pressures for the high densities) EOS models that have been proposed in the literature. Given its high frequency and time resolution, the ALFA pulsar survey will be able to detect any sub-millisecond pulsars in an unprecedented volume of useful space.

Another way of constraining the EOS is by measuring the masses of MSPs in binary systems. Millisecond pulsars were spun up by a prolonged accretion of matter from a companion star. It is not clear how much mass can be accreted, but there are no *a priori* reasons to exclude transferred masses of 1 $M_\odot$ or more. In the "soft" EOS models (where dense matter is more compressible), neutron stars become unstable against collapse above 1.6 $M_\odot$; in some of the "hard" models the limit is 2.5 $M_\odot$. Finding a single neutron star with a mass significantly above 1.6 $M_\odot$ can exclude many "soft" EOS models. This is apparently the case for PSR B1516+02B, in the globular cluster M5B, for which Freire et al. (2007) find a mass of $(1.96^{+0.08}_{-0.12})M_\odot$.

Synergy with Gravitational Wave Observatories: Advanced LIGO will come on line around 2013 and LISA, the Laser Interferometer Space Antenna, may launch some time in the second half of next decade. There is tremendous synergy between radio studies of compact objects and gravitational wave targets:

1. A steady sequence of NS-NS binary discoveries with Arecibo and other instruments will tighten the estimate of binary merger rates, relevant for predictions for advanced LIGO.
2. The MSP pulsar timing array may yield the first direct detection of gravitational waves by sampling the nano-Hertz band. The most likely signal — background waves from merging, supermassive black holes — may extend into the LISA band, which will provide both confirmation and evaluation of the spectral shape of this particular background signal.
3. Discovery and timing of new pulsars, particular those with the fastest spins, will provide explicit targets for advanced LIGO and even for the upgraded LIGO that will come into operation around 2009. Interesting limits are already being placed on NS ellipticities. New objects with large spins and/or large magnetic fields (which can cause distortions of the NS crust) are the most interesting targets. Arecibo can find objects suitable for these studies and can conduct the necessary timing observations that enable the LIGO studies.
4. LISA will be able to detect gravitational waves with periods ranging from many hours to a fraction of a minute. It has guaranteed sources of gravitational waves, but the most interesting sources will probably be those we don't know about yet. One particular feature of this mission is very relevant to our purposes; its ability to detect extremely compact systems. LISA will detect binary systems (NS-NS and NS-BH) too compact to easily be found in radio surveys. Thus LISA-selected binaries will require followup radio obserations, which will be enabled by localization of the source from the LISA observations.
5. Technique development: many of the detection schemes in both radio pulsar and gravitational wave detection are applications of matched filtering. Some, such as detection of chirped signals, are explicitly in common. The intersection of common science goals and methods to achieve them is an area where radio and gravitational-wave astronomers can collaborate.

Instrumentation and Techniques

The pulsar/compact-objects program sketched here implies development of telescope instrumentation, processing backends and technique development. These include:

1. **Improving timing precision:** Arecibo's sensitivity is the foundation for timing precision, but so too is polarization calibratibility of wideband feeds, actual calibration of data from such feeds, and development of extended matched filtering techniques that take pulse fluctuations and propagation effects into account. A concerted program of timing precision should commence.
2. **Deployment of broadband feeds:** work on the SKA is proceeding on development of broadband feeds, i.e. with 5:1 or 10:1 frequency ratios. Using such feeds on Arecibo will provide unprecedented signal-to-noise ratio and unprecedented ability to track and remove frequency-dependent propagation effects (dispersion and scattering). In addition, estimators can be developed that use a weighting function vs. frequency that optimize against scintillation fluctuations and RFI. Polarization purity of broadband feeds is essential.
3. **Development of post-ALFA multiple-pixel systems:** blind surveys, of both the Galactic disk and outside the disk, are enhanced by multiple pixel systems. For steeper spectrum sources, surveys below the ALFA band can be made concurrently with galaxy HI surveys, which are also being considered in order to reach higher redshifts, e.g. in the 0.9 to 1.2 GHz band. Higher-frequency phased-array feeds, if viable, may be required for unbiased surveys of flat-spectrum magnetars that turn on with poorly known duty cycles.
4. **Advanced pulsar backends:** current technology trends suggest that samplers and processors can be built that can handle any and all accessible radio-frequency bandwidth provided by Arecibo (or the GBT). Next generation systems that handle 1 to 4 GHz (say) of bandwidth for both post-detection and coherent dedispersion will enable truly optimized survey observations and timing precision.
5. **Synergistic science and technology development with the FAST project:** Arecibo pulsar surveys will have progressed significantly by the time FAST comes on line ($\gtrsim 2013$) and can serve as a roadmap for FAST's follow-on surveys and for providing pulsars in need of timing by FAST. Prior to this, joint effort between NAIC and the FAST project can involve development of feed and receiver systems as spinoffs, for example, of work being done for SKA development.

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