High Precision Pulsar Timing at Arecibo Observatory

What are pulsars? When the cores of massive stars run out of nuclear fuel they collapse catastrophically. Their immense gravitational field, now unopposed, crushes the core material so hard that even its atoms are destroyed. This powers a phenomenon known as a *supernova*.

The supernova event marks the birth of a *neutron star*: what remains of the core is a ball of neutrons, a single giant atomic nucleus with a radius of about 10-16 km and more than 400 000 times the Earth's mass. Their densities are hundreds of millions of tons per cubic cm.

Many of them emit beams of radio waves through their magnetic poles. As they rotate, their beams sweep through space. If the Earth happens to be in a direction swept through by these radio beams, then we can detect a periodic series of radio pulses, i.e., the neutron star is then detected as a *pulsar*. This is similar to observing the periodic flashes of a lighthouse light.

What is a millisecond pulsar? The fastest-rotating pulsars rotate several *hundred times per second*. These pulsars were spun up through accretion of mass and angular momentum from binary star companions. Most observed millisecond pulsars (MSPs) have evolved beyond the accretion stage and are simply fast-spinning pulsars, most of them are in binary systems with white dwarf companions.

What is pulsar timing? Pulsar timing is the measurement of times at which pulses from a given pulsar arrive at a radio telescope. Arrival times can be measured very precisely—with precision better than 100 ns in the best cases (averaged over a typical observation of half-hour duration). MSP rotation is extremely stable, so the pulse arrival times are very regular and predictable—in the best cases, they can be predicted with accuracy of better than a microsecond over many years. Thus MSPs act as superb astrophysical clocks, emitting "ticks" with extreme regularity. Pulse arrival times are affected by various phenomena described in Figure 1; this in turn allows pulsar timing to be used for a wide variety of scientific applications summarized below.

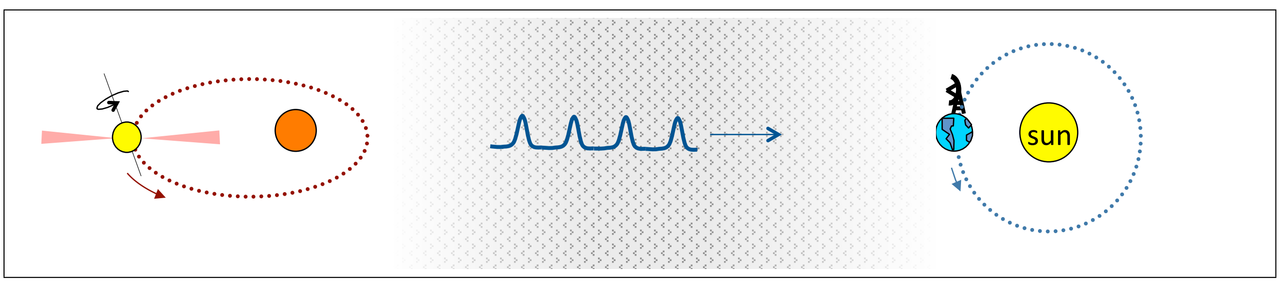

Figure 1: The pulsar, on the far left, emits beams of radio waves, which are later detected at a radio telescope on Earth. Any effects that *change* the times of arrival of the radio pulses at the radio telescope can be studied with exquisite precision, such effects can be used for a wide variety of scientific applications described in the text.

These effects include: the orbital motion of the pulsar (if it is in a binary system), its motion through space and the motion of the radio telescope relative to the Solar System Barycenter. The arrival times are also affected by the passage of the pulses through ionized material, which slows the propagation of the pulses in a manner which depends on the radio frequency. This ionized material can be in both the interstellar medium, the solar wind and the Earth's ionosphere. Finally, the arrival times can be perturbed by distortions of spacetime caused by gravitational waves passing through the location of the pulsar or the location of the Earth.

Some scientific applications of pulsar timing - And Arecibo's role in them.

The precision of pulse arrival time measurements depends directly on the gain of the telescope used. As the largest radio telescope in the world, with a gain 5 times larger than the next-best instruments, the Arecibo 305-m telescope can make the most precise measurements of any pulsar within its declination range, $-1^\circ < \delta < 38^\circ$. For all the scientific applications listed below, this timing precision is absolutely crucial:

- Searching for direct evidence of gravitational waves by measuring quadrupolar perturbations on the local space-time metric. *Currently, Arecibo provides the most stringent constraints on low-frequency gravitational waves.*
- Measuring the radiative properties of gravity by studying the orbital decay of binary pulsars. Double neutron stars provide excellent tests of general relativity (GR). MSP - white dwarf binaries are even better suited for constraining theories of gravity other than GR. *The best constraints on alternative gravity theories have all been derived from Arecibo timing!*
- Timing the recently discovered triple system will allow a 4 order of magnitude improvement in tests of the strong equivalence principle. *The best timing of this system is being done at Arecibo!*
- Measurement of neutron star masses constrain nuclear physics at densities higher than that of the atomic nucleus. *The most massive NS known will very soon have very precise mass measurements - thanks to Arecibo timing measurements!*
- Studying the astrophysics of binary system evolution. This benefits greatly from the study of exotic binary systems, such as MSPs with low-mass companions ablated by pulsar winds, MSPs with planet-mass companions, three-body systems and a new class of MSPs with eccentric orbits - *all systems from the latter three classes are detectable from Arecibo*.

The precision of pulsar timing at Arecibo has improved dramatically in the last two years! For precise timing, the effect of interstellar dispersion must be removed by the process of "coherent dedispersion." This is computationally intensive. The introduction in 2012 of the PUPPI data acquisition system allows for an order-of-magnitude increase in radio bandwidth (figure 2).

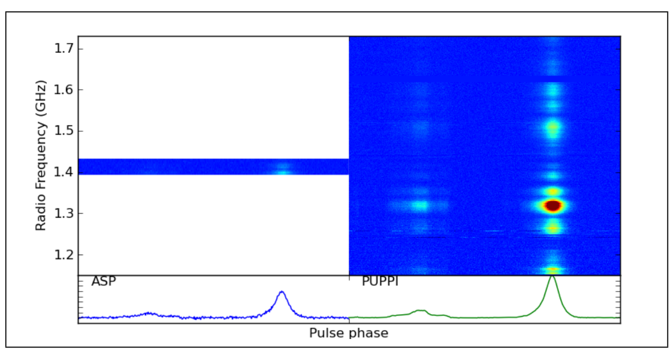

Figure 2: Example of data collected at Arecibo observatory in March 2012 showing the signal collected with the best previous-generation instrument, ASP (left, 64 MHz bandwidth) and the new state-of-the-art instrument, PUPPI (right, 800 MHz bandwidth). Data from PSR J2214+3000. Each of the upper plots shows pulse phase on the horizontal axis and radio frequency on the vertical axis. The pulsar strength varies across the band due to interstellar scintillation. Each of the lower plots shows the pulse profile after summing across all observed frequencies. Because ASP missed the bright "scintle" near 1300 MHz, its signal-to-noise ratio is about an order of magnitude worse than PUPPI. (Figure credit: Paul Demorest)

Extended discussion with references

1 Overview

In this part of the white paper, we give more detail on various applications of pulsar timing. We give short summaries of the topic, followed by some key references, emphasizing work using the Arecibo Observatory. Here are some background references on pulsars, millisecond pulsars and pulsar timing:

- Background information on pulsars in general:
  Lorimer, D. R., & Kramer, M. 2005, Handbook of Pulsar Astronomy (Cambridge University Press)
- Review of millisecond and binary pulsars:
  Lorimer, D. R. 2008, Living Reviews in Relativity, http://relativity.livingreviews.org/Articles/lrr-2008-8/
- Review of pulsar timing techniques.
  Lommen, A. N., & Demorest, P. 2013, Classical and Quantum Gravity, 30, 224001

There is an old adage that "past performance is not a guarantee of future results." However, the pulsar searching-and-timing effort has been consistently producing unexpected, exciting new results for many decades. The biggest discoveries—the first binary pulsar, the first millisecond pulsar, the first pulsar planets—were all completely unanticipated. Searches for new pulsars have rarely disappointed.

2 Studying the properties of gravitation and space-time

Pulsars in compact binary systems provide excellent laboratories for studying and testing relativistic theories of gravity. These include tests of the radiative properties of gravity (section 2.1), tests of the strong equivalence principle (section 2.2) and local Lorenz invariance of gravity (section 2.3).

For a broad and up-to-date review on these, see:
Wex, N. 2014, ArXiv e-prints, (astro-ph/1402.5594)

2.1 Testing the radiative properties of gravity

Relativistic phenomena observable in the orbits of some binary pulsars include relativistic precession of periastron ($\dot{\omega}$); variations in time dilation and gravitational redshift over the course of the orbit (γ); decay of the orbit due to energy and angular momentum lost by emission of gravitational waves ($\dot{P}_b$); delay of the pulsar signal as it passes through the potential well of its companion star (Shapiro delay), and geodetic precession of the pulsar orientation, resulting in changes in the observed pulse shape.

Classical tests of general relativity: These tests were done with compact double neutron star systems.

- The first binary pulsar ever discovered (B1913+16, the famous Hulse-Taylor pulsar) was found in an Arecibo survey in 1974. Continued Arecibo timing allowed precise mass estimates from the measurements of $\dot{\omega}$ and γ (assuming GR).

  This allowed a precise prediction of the orbital decay ($\dot{P}_b$) due to the emission of gravitational waves as predicted by GR. This effect was eventually measured precisely, and it matches the GR prediction to high numerical precision. This provided unequivocal evidence for the existence of gravitational waves, and started a whole new area in astronomical research. For this achievement, Russel Hulse and Joseph Taylor were awarded the Nobel Prize in Physics in 1993.

  - *Hulse, R. A., & Taylor, J. H. 1975, ApJ, 195, L51*
  - *Taylor, J. H., & Weisberg, J. M. 1989, ApJ, 345, 434*
  - *Weisberg, J. M., Nice, D. J., & Taylor, J. H. 2010, ApJ, 722, 1030*

- Orbital decay has also been detected in several other double neutron star systems; here are some representative examples from Arecibo observations.

  - *Jacoby, B. A., Cameron, P. B., Jenet, F. A., et al. 2006, ApJ, 644, L113*
  - *Fonseca, E., Stairs, I. H., & Thorsett, S. E. 2014, ApJ, 787, 82*
  - *van Leeuwen, J., Kasian, L., Stairs, I. H., et al. 2014, ArXiv e-prints, (astro-ph/0207156)*

Limits on dipolar gravitational wave emission: These new tests are being carried out with MSP-WD systems.

For these systems, measuring $\dot{\omega}$ and γ is generally impossible, given the very low eccentricities of their orbits. For this reason, measuring MSP masses and using them for tests of gravity theories has not been feasible until very recently.

- However, in some cases, notably PSR J1738+0333 and PSR J0348+0432, the companion WDs are relatively bright. Their spectroscopy yields measurements of the WD mass ($m_{\rm WD}$) and the mass ratio (q); both yield the pulsar mass. As for the previous systems, this allows a prediction of $\dot{P}_b$.

  These binary systems are also among the most compact MSP-WD systems known. This means that their small predicted $\dot{P}_b$ has been measured precisely - this was only possible because of the precise Arecibo timing. The observed values match the GR prediction.

  - *Antoniadis, J., van Kerkwijk, M. H., Koester, D., et al. 2012, MNRAS, 423, 3316*
  - *Freire, P. C. C., Wex, N., Esposito-Farèse, G., et al. 2012b, MNRAS, 423, 3328*
  - *Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, Science, 340, 448*

  The important point of these measurements is that, for these "asymmetric" MSP-WD systems, many alternative theories of gravity predict the emission of *dipolar gravitational waves* (DGW). The difference between the observed and GR-predicted $\dot{P}_b$ is so small that these systems yield the most constraining limits on DGW emission. These limits, all based on Arecibo timing, yield the *most constraining limits ever on several classes of alternative theories of gravity*, like the Scalar-Tensor theories of gravity and a wide family of theories similar to the Tensor-Vector-Scalar (TeVeS) theory proposed by Bekenstein in 2004.

- The radiative test in PSR J0348+0432 was the first one ever done for a super-massive neutron star, i.e., *these Arecibo timing measurements are, for the first time, testing the radiative properties of gravity in a new regime of extreme gravitational forces and binding energy*. This measurement has also greatly improved our confidence in the mathematical templates to be used by LIGO and VIRGO to detect the coalescence of double neutron star and black hole - neutron stars systems for the whole range of neutron star masses.
  Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, Science, 340, 448

2.2 Strong equivalence principle

The strong equivalence principle (SEP) asserts that the motion of a body under gravitation does not depend on the composition of that body. This is a fundamental feature of general relativity; therefore detecting SEP violation would falsify GR. Neutron stars allow unique SEP tests because their strong negative binding energy makes their gravitational masses significantly different than their baryonic masses.

- The newly discovered MSP in a triple star system, PSR J0337+1715, will allow a search for SEP violation with unprecedented sensitivity. Arecibo observations are already contributing strongly to the timing solution for the MSP, since they provide the most precise timing measurements.
  Ransom, S. M., Stairs, I. H., Archibald, A. M., et al. 2014, Nature, 505, 520
- A review article describing strong equivalence principle pulsar experiments before the discovery of the triple system. This also suggests how such a system might be used for SEP tests.
  Freire, P. C. C., Kramer, M., & Wex, N. 2012a, Classical and Quantum Gravity, 29, 184007

2.3 Local Lorenz Invariance of gravity

In fully conservative theories of gravity (like Scalar-Tensor and GR) the gravitational interaction has no preferred reference frame, i.e., they are locally Lorenz invariant (LLI). Detecting LLI violation would, again, falsify not only GR, but all the conservative theories of gravity.

- Based on the constraints derived from the optical work on of PSR J1738+0333 (which yield the inclination and 3-D velocity) and the incredibly small eccentricity (measured by the Arecibo radio timing), Lijing Shao and Norbert Wex have derived the best constraint on α_1, one of the parameters that describes local Lorentz invariance violation of gravity: ($\alpha_1 = -0.4^{+3.7}_{-3.1} \times 10^{-5}$, 95% C.L.). This constitutes a factor of 5 improvement compared to all previous limits, either from binary pulsars or Solar System tests. Furthermore, this limit will improve much faster with time (with $T^{-3/2}$, where T is the timing baseline) than the limits from Solar System tests.
  Shao, L., & Wex, N. 2012, Classical and Quantum Gravity, 29, 215018
- In an important recent paper, the LLI limits listed above, plus the Arecibo timing of PSR J1738+0333, J0348+0432, the "Double Pulsar" and PSR J1141−6545 were used to constrain the Einstein-Æther and Hořava gravity theories to the point that the surviving theories predict NS-NS mergers undistinguishable from those of GR. These theories were among the few well-studied and well-motivated alternatives to GR that were candidates for testing by advanced LIGO and Virgo.
  Yagi, K., Blas, D., Barausse, E., & Yunes, N. 2014, Phys. Rev. D, 89, 084067

3 Direct detection of gravitational waves

Gravitational waves passing by a pulsar or the Earth perturb the time-of-flight of pulsar signals from the pulsar to the observatory. Detecting these perturbations would constitute, for the first time, the *direct* detection of gravitational waves. (To date, they have only been indirectly detected, via pulsar timing measurements of decaying binary orbits.)

In order to distinguish a gravitational wave signal from pulsar rotation irregularities, the signal must be seen in multiple pulsars. The first detection of gravitational waves by pulsar timing is likely to be a stochastic background of gravitational waves emitted by binary supermassive black holes scattered across the Universe. For this application, the optimal detection method involves observations of many pulsars (a "pulsar timing array") and cross-correlating their arrival times. Such observations are presently underway at Arecibo and the Green Bank Telescope by the NANOGrav collaboration.

The stochastic gravitational background is expected to have a highly red spectrum, so that it is dominated by waves of the longest detectable periods (many years). For this reason, the sensitivity of pulsar timing to gravitational waves improves dramatically as the data span is increased.

- A stringent upper limit on a gravitational wave background from five years of pulsar timing at Arecibo and Green bank.
  Demorest, P. B., Ferdman, R. D., Gonzalez, M. E., et al. 2013, ApJ, 762, 94
- An upper limit on gravitational waves due to individual sources.
  Arzoumanian, Z., Brazier, A., Burke-Spolaor, S., et al. 2014, ApJ, 794, 141
- A description of the NANOGrav collaboration
  McLaughlin, M. A. 2013, Classical and Quantum Gravity, 30, 224008
- Scaling laws and time to detection for pulsar timing arrays.
  Siemens, X., Ellis, J., Jenet, F., & Romano, J. D. 2013, Classical and Quantum Gravity, 30, 224015

4 Neutron star masses

Neutron stars consist of matter at nuclear densities and provide the only observational means of studying such matter on scales larger than individual atoms. The intense pressures at the cores of neutron stars may result in the formation of exotic forms of matter beyond conventional nucleons. The primary measurable quantities provided by pulsar timing are masses of neutron stars, which have now been measured to range from 1.3 solar masses up to 2.0 solar masses or more. The latter "heavy neutron stars" have particularly large central pressures, which would tend to cause neutron stars to collapse if they were made of "soft" material such as de-confined quarks, thus constraining the allowed theoretical equations of state.

- A comprehensive review of neutron star physics, which includes a detailed discussion of the constraints on the properties of super-dense matter introduced by the measurement of massive neutron stars.
  Lattimer, J. M. 2014, General Relativity and Gravitation, 46, 1713
- A $2.01 \pm 0.04\,\mathrm{M}_{\odot}$ pulsar being observed at Arecibo. The mass of this pulsar was determined by optical spectroscopy. However, soon the measurement of $\dot{P}_b$ for this system - a result

of Arecibo timing of this pulsar - will be so precise that if we assume that it is ongoing as predicted by GR and combine this with the precisely measured and theory-independent mass ratio (q), we will have a much more precise mass for the pulsar. This will therefore be a very solid constraint on the properties of super-dense matter.
Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, Science, 340, 448

5 Stellar evolution

The Arecibo telescope has recently witnessed many new exciting developments in the study of the evolution of binary pulsars:

- Some of these confirm the standard scenarios for the formation of MSPs. PSR J1023+0038 represented the long-sought transition between low-mass X-ray binaries (LMXBs) and MSPs. This system is being routinely timed at Arecibo:
  Archibald, A. M., Stairs, I. H., Ransom, S. M., et al. 2009, Science, 324, 1411
- Other systems are so bizarre that they don't conform to any expectations of stellar evolution theory. One prominent example is PSR J1903+0327, discovered in the Arecibo ALFA pulsar survey. This is a MSP with a main-sequence companion similar to the Sun in a wide ($P_b = 95$ day) and eccentric ($e = 0.44$) orbit.
  Champion, D. J., Ransom, S. M., Lazarus, P., et al. 2008, Science, 320, 1309
- A deep study of this system using Arecibo timing data and spectroscopic optical observations of the companion has demonstrated that this system very likely formed in a triple system, which was later disrupted:
  Freire, P. C. C., Bassa, C. G., Wex, N., et al. 2011, MNRAS, 412, 2763
- The formation of MSPs in triple systems has now been confirmed beyond all doubt:
  Ransom, S. M., Stairs, I. H., Archibald, A. M., et al. 2014, Nature, 505, 520
- However, new systems and new questions continuously emerge. Three new MSPs, J1946+3417, J1950+2414 and J2234+0611 (all visible in the Arecibo sky, two of them discovered with Arecibo) have eccentric orbits (all with $e \sim 0.1$), low-mass WD companions and very similar orbital periods (22-32 d):
  - *Barr, E. D., Champion, D. J., Kramer, M., et al. 2013, MNRAS, 435, 2234*
  - *Deneva, J. S., Stovall, K., McLaughlin, M. A., et al. 2013, ApJ, 775, 51*
- These systems might have all originated as triple systems, but the close similarity of them all is not to be expected from the chaotic destruction of a triple. More radical scenarios have been proposed, like rotationally-delayed accretion induced collapse of a massive, supra-Chandrasekhar WD:
  Freire, P. C. C., & Tauris, T. M. 2014, MNRAS, 438, L86
- However, the latest Arecibo mass measurements for these systems do not confirm the latest scenario. The mystery deepens...

6 Improved instrumentation

Many of the results discussed above depend crucially on the timing precision that can be achieved for the relevant systems. In order to improve it, the best possible instrumentation is required. The best technique for pulsar timing is known as *coherent dedispersion*.

Because the propagation speed of radio waves in the interstellar medium is frequency dependent, radio power emitted simultaneously across the band at the source (pulsar) is convolved with a chirp function, so that pulses arrive later at lower frequencies. The signal can be de-convolved almost perfectly, but this must be done in the Fourier domain, which is a computational expensive task. For this reason, until recently this could only be done for very small bandwidths.

In modern pulsar data acquisition systems, this is done using combinations of clusters of computers, programmable gate arrays, and/or graphics processing units. To make data storage tractable, the signal also must be folded with the pulse period, which is a computationally complex processes since the period continually changes as the pulsar and Earth more relative to one another. At Arecibo, PUPPI (Puertorican Ultimate Pulsar Processing Instrument) performs these tasks for an unprecedented bandwidth of 800 MHz. It is based on open source CASPER FPTA hardware and software, coupled to a cluster of GPUs.

- Description of Green Bank pulsar data acquisition system GUPPI; the Arecibo data acquisition system PUPPI is nearly identical.
  DuPlain, R., Ransom, S., Demorest, P., et al. 2008, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7019, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 70191D
- Much of the hardware for the PUPPI and other modern instruments uses hardware developed by CASPER, which develops high-throughput hardware and software for a variety of radio astronomy applications.
  http://casper.berkeley.edu

Thanks to PUPPI, pulsar timing at Arecibo is undergoing a renaissance, particularly for faint, distant MSP, which can now be clearly detected and precisely timed.

7 Other topics traditionally addressed at Arecibo

- Studying the radio properties of pulsars. Indeed, with its unique sensitivity, Arecibo has allowed unprecedented studies of the pulsar radio phenomenology.
- Neutron star kinematics. Timing measurements and VLBI experiments have measured the proper motions for many pulsars. This has revealed the large kick velocities imparted on them by the supernova events that form them.
- Probing the properties of the ionized interstellar medium. Pulsars allow direct measurements of the electron column density along their lines of sight. From this; maps of the electron density in the Galaxy have been derived.
  Cordes, J. M., & Lazio, T. J. W. 2002, preprint (arXiv:astro-ph/0207156)