Probing Fundamental Pulsar Physics at Arecibo, the World's Most Sensitive Radio Telescope

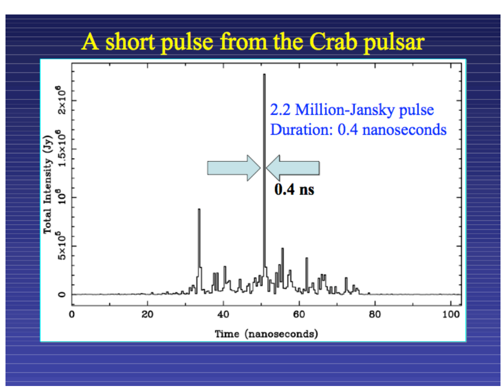
Pulsars are city-sized stars with as much material as the Sun. Rotating many times each second, they are surrounded by huge magnetic fields that in turn induce enormous electric fields. Pulsars generate radio frequency emissions from regions above their magnetic poles, appearing as radio "light houses". The physical conditions near and within pulsars are some of the most "exotic" in the cosmos; thus their study provides key tests of the fundamental principles of physics. These "almost black holes" generate powerful beams of radio energy by processes similar to the Earth's aurorae, but unimaginably more intense. The Arecibo telescope's unrivaled sensitivity has kept it at the forefront of pulsar investigations for the past four decades.

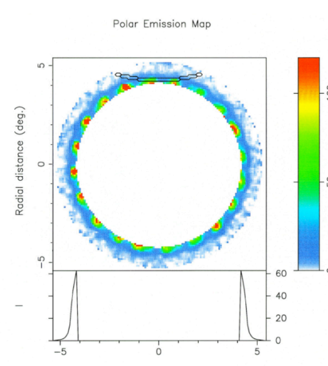
Arecibo is providing most of the key discoveries about pulsar physics, including:

- discovery of fundamental phenomena: "drifting" subpulses, nulling, and microstructure.
- identification of the double-cone and core characteristic pulsar beam forms.
- confirmation that the emission cones are comprised of multiple subbeams that precess around a pulsar's magnetic pole.
- the physical significance of the orthogonal polarization modes and null periodicities.
- moding studies prompting simultaneous radio and X-ray satellite investigations
- nano-arc-second imaging of pulsar emission beams using both natural interferometers in the interstellar medium and subbeam-circulation mapping
- ultra-wide-band observations of pulsars revealing basketball-sized emission elements
- microstructure polarimetry showing moding and parent microstructure
- precision polarimetry showing absolute alignments and physical propagation modes

Pulsars' enormous magnetic, electric and gravitational fields provide "exotic" conditions for testing physical principles that occur nowhere else in the universe. Only Arecibo can:

- conduct investigations of important WEAK and DISTANT PULSARS (*e.g.*, B0943+10 below).
- obtain sensitive measurements of the DYNAMIC POLARIZATION OF PULSAR SIGNALS.
- carry out DETAILED OBSERVATIONS of the properties of BRIGHT PULSARS.

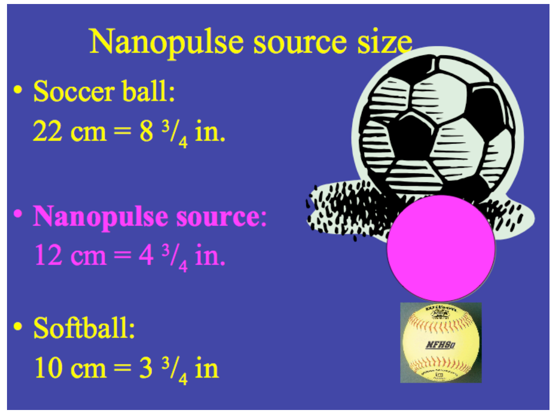




Left: Optical image of the Crab Nebula, a nearby supernova in 1054, where Arecibo identified the then fastest spinning pulsar in 1968. **Center**: A giant pulse from the Crab pulsar, over extremely short times the brightest signal known. **Right**: Subbeam emission "carousel" of pulsar B0943+10 that rotates around its magnetic axis every 43 seconds producing its "drifting" subpulses, identified using Arecibo.

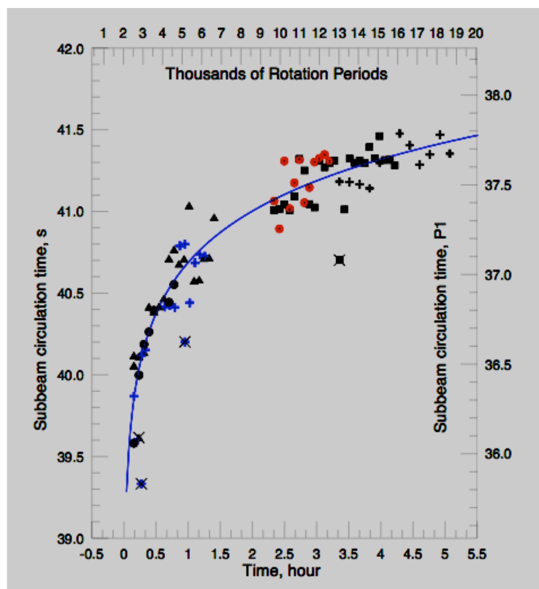
Arecibo continues to reveal unique and exotic aspects of pulsar radiation that illuminate fundamental physics and are beyond the reach of all current and planned telescopes.

The Brightest Pulses in the Galaxy



"What is the physics behind the conversion of a pulsar's rotational energy to the radio emission we see as regular pulses similar to what one sees from the rotating beam of a lighthouse?" One hypothesis is that violent turbulence in the highly charged pulsar atmosphere produces bursts of radiation, which could then be seen as very short radio pulses. Using a technique to remove the distortion of pulsar radio signals due to propagation through the huge distance of interstellar space, the predicted short pulses have been found in signals recorded with ultra-high time resolution at the Arecibo Observatory. To produce a short pulse, an emitter can be no larger than the distance light travels in the duration of the pulse. "Nanopulses" as short as 4 ten-billionths of a second (0.4 ns, see above) have been detected from the Crab Nebula pulsar. With instantaneous energies as powerful as the Sun (whose radio intensity is a million Janskys—though typical radio sources are only a few Janskys), but a billion times further away, these nanopulses are the brightest cosmic signals ever measured. Thus, the emitter must be larger than a softball and smaller than a basket ball—*i.e.*, about 12 cm (see above). The next challenge for understanding pulsar emission physics is to determine if other pulsars have similar characteristics. Ultra-high time resolution measurements made with the Arecibo telescope are required to test this hypothesis.

The Physics of Carousel Subbeam Systems



Pulsars' characteristic cones of emission, Arecibo studies now show, are produced by "carousels" of rotating subbeams that also produce their "drifting" subpulses and most "null" pulses (see above figure). Typical circulation times are a minute or more, and these probe the physically crucial high field regions just above a pulsar's magnetic polar cap. After onset, the "drift" circulation time in pulsar B0943+10 has been found to decay with a characteristic time of about one hour—the longest orderly behavior seen in any pulsar phenomenon. Satellite x-ray observations prompted by this result show a surface temperature of 500,000 degrees on the star's polar cap. Changes may produce the circulation-time recovery, revealing a fundamental property of pulsar radiation physics.

Further Arecibo investigations have identified evidence of subbeam carousel systems in many other pulsars. Periodic cessations of emission can now be understood as due to partially filled carousels, and the prominent multiple drift modes—such at that in Arecibo pulsar B1918+19—are well understood in terms of carousels with several different stable subbeam configurations.

Probing Fundamental Pulsar Physics using Arecibo, the World's Most Sensitive Radio Telescope

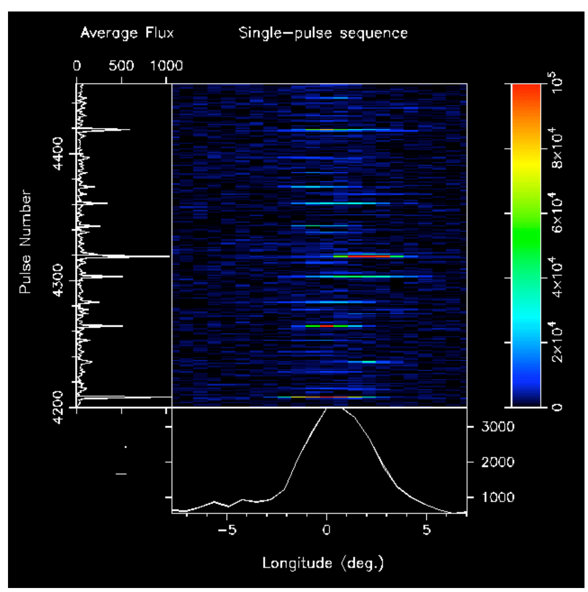
by Paul Demorest, Timoth Dolch, Timothy Hankins, Dipanjan Mitra & Joanna Rankin

Raw Sensitivity in Service of Many Different Kinds of Measurements

The great sensitivity of the Arecibo lends inself to many different kinds of detections and studies. Investigations of the unique and exotic physical mechanisms of the pulsar emission regions is sensitivity limited, so Arecibo's broad band and much larger collecting area is almost always crucial. Most radio telescopes can measure little more than the average properties of pulsar emission, but at Arecibo measurements can be conducted on much finer time scales in some cases down to the microsecond or even nanosecond level—thus probing completely different regimes of physical phenomena. Only by using Arecibo can questions be asked about whether millisecond pulsar emission is different from that of the slower pulsars. Only at Arecibo might we expect to detect pulsars from more distant galaxies. Only at Arecibo can observations be made of many pulsars at time resolutions revealing their microstructure. Studies of pulsar nulling and flaring both benefit greatly from Arecibo's great sensitivity, the first to distinguish weak pulse emission from true cessations and the latter probe the dynamic range of flares in weak pulsars.

Absolute Radio Polarimetry

Arecibo has one of the most accurate and flexible polarimetry capabilities of any instrument in the world. This facility has been used to study the polarization of pulsar radiation in multiple ways that lead to insights about the physical processes responsible for pulsar radiation. Not only are the polarimeters capable of measuring the amount of linear and circular polarization, they are also able to refer the polarization angles to the intrinsic polarization angle on the sky and ultimately to the orientation of the polarization relative to the magnetic field in the emission region of the pulsar. All polarimetry is strictly limited by sensitivity because the signal must exceed the noise if the polarization position angle is to be meaningful, so Arecibo is able to make single pulse polarization measurements on a far larger population of pulsars than any other instrument, including some millisecond pulsars. Arecibo can make polarization measurements at different intensity levels on a given pulsar and achieve the needed sensitivity to study the two orthogonal polarization modes of many pulsars separately. This technique has proven to be crucial in discovering and investigating the intensity-dependent aberration/retardation and resulting depolarization that is exhibited by some core emission.



Quasiperiodic subpulses and giant pulses from millisecond pulsar B1534+12. Only Arecibo has the raw sensitivity to conduct analyses such as this on the fast, weak millisecond pulsars that are critically important for such precision pulsar timing programs as NANOGrav.

Wide Bandwidths and Frequency Versatility

Arecibo is not only sensitive in terms of collecting area, the instrument also achieves sensitivity through wide bandwidths and very low noise receivers. The Arecibo reflector has been fared to a precision of about 2 mm, making it usable up to a frequency of at least 10 GHz. Pulsars are usually studied in the spectral region between a few hundred MHz and 2 GHz, but its facility in conducting observations over this broad band make the instrument particularly capable. The results of nanosecond observations of the Crab pulsar reported above required 2 GHz bandwidth. Very high frequency single pulse observations of some pulsars promise to provide a tomographic window on emission-region processes. Polarimetry over this unusually wide bandwidth makes the instrument able to probe high rotation measures including effects within the magnetosphere itself.

Arecibo Remains Unique in the World for the Foreseeable Future

- able to study the emission dynamics of the weakest and most distant pulsars currently known. Therefore, many exciting investigations can only be pursued using Arecibo.
- the only telescope currently capable of investigating pulsar depolarization processes dynamically and at high resolution.
- the most sensitive telescope for studying high time resolution phenomena, which are often the most exciting for tests of fundamental physics.

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