Tests of Gravity and Neutron Star Properties from Precision Pulsar Timing and Interferometry

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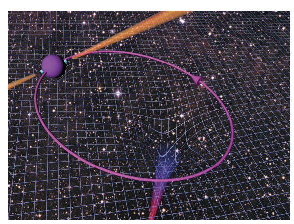

Synopsis of Key Questions and Measurement Program

This whitepaper concerns questions about gravity and dense matter in relativistic stars:

- **What is the correct theory of gravity on stellar scales in strong fields?**
- **What is the best description of matter at nuclear densities and higher?**

Addressing these questions also raises a natural astrophysical question:

- **What are the merger rates of compact objects in the Milky Way and what are the implications for gravitational wave events and gamma-ray bursts?**

Answers to these questions are based on pulsar-timing metrology of binary systems whose compact orbits require a post-Newtonian description. The current state of the art can detect first-order relativistic effects (with magnitude $\sim 1\,\mu$s) and the prospects are excellent for measuring smaller effects in common systems. The prospects are excellent for finding binaries much more compact than the known ones and potentially with much greater companion masses (e.g. pulsar-black-hole binaries).

A **Galactic census** of neutron stars is the first stage of the program to find new pulsars in dynamically-clean binaries. Of order 100 or more double neutron star (DNS) systems can be expected with suitable instrumentation. Black hole companions are evidently much rarer; they have eluded detection owing to sensitivity and data processing limitations. Millisecond pulsars by the thousands will provide a definitive spin-period distribution that will elucidate the physics of NS structure and gravitational-wave effects that determine the minimum spin period. The census requires high-sensitivity telescopes operating pan-chromatically in the radio, optical, X, and gamma-ray bands, with special emphasis on centimeter wavelengths. New telescopes are needed to sample the Milky Way for most of the radio luminosity function. High-time-resolution spectrometers provide data suitable for removal of interstellar dispersion distortion. High-performance computing is needed to remove orbital delays of compact binaries before employing a Fourier-based detection algorithm. Excision of radio frequency interference requires deployment of techniques from a continuing program of algorithm development.

Pulsar timing yields the orbital elements to high precision and, depending on the object, selected post-Keplerian parameters. Together, these determine the individual stellar masses to high precision while also constraining theories of gravity in strong-field regimes quite different from solar system tests. Particularly important constraints are made on the maximum mass of neutron stars, the Strong Equivalence Principle, preferred-frame effects, the existence of dipolar gravitational radiation, and secular changes in the gravitational constant. Precision timing requires well-calibrated pulse profiles (both for timing and for relativistic spin-axis precession studies) along with high-quality time transfer and time tagging methods. Continued technique development is needed to mitigate pulse distortions and delays intrinsic to pulsar magnetospheres and from intervening plasmas. These measurements must be made over a 2:1 wavelength range to remove highly chromatic plasma effects.

The **astrometry** program is crucial for theory of gravity tests because kinematic corrections to the timing equation have distance and velocity dependent terms. While astrometric information emerges from the timing analysis itself, very long baseline interferometry (VLBI) is needed to obtain parallaxes in most cases. Parallax distances provide key kinematic corrections to observed orbital evolution, necessary for comparison with GR and other theories of gravity. With current dedicated VLBI arrays, distances up to 5 kpc have been reached, but only for the brightest sources. A large-scale parallax program will require more sensitive telescopes. The GAIA and SIM astrometric missions will provide distances to nearby white dwarfs useful for millisecond pulsar timing.

Context for Testing Theories of Gravity

Theories of gravity have been tested in the solar system and show consistency with General Relativity to high precision. Observations of binary stars, particularly pulsars, also show consistency with GR in regimes of strong gravity not available in the solar system, allowing many theories to be ruled out. On Galactic and cosmological scales, Newtonian gravity and General Relativity are often assumed to hold, but it is well recognized that modifications of gravity may play a role in the interpretation of astronomical measurements relevant to dark matter and dark energy. Also, a beyond-GR approach is demanded by the need to meld quantum mechanics and gravity into a theory that would apply to the early universe. It is therefore appropriate to seek the first departures from GR using objects and tools that are in hand and capable of improvement by several orders of magnitude.

Electromagnetic radiation from neutron stars (NS) is a superb probe of density regimes and strong gravity not yet accessible by other means. Once gravitational waves (GWs) are detected in the mHz to kHz range by ground and space-based detectors, NS and black-hole (BH) astrophysics will enter a new realm. Even then, however, EM approaches will provide unique information, as discussed here. Pulsars are objects with strong gravity by virtue of their size being only a factor of three larger than their gravitational radius. Consequently, strong-field phenomena appearing in pulse timing measurements can place constraints on a wide variety of relativistic theories, including tensor-multiscalar descriptions of gravity (Damour 2007). NS are found with a large range of companions types, including the triumvirate of white dwarfs, other neutron stars, and—potentially—stellar-mass black holes. These allow tests of equivalence principles using, for example, the Nordvedt effect that depends on differences in inertial and gravitational masses for objects of different composition. Timing of pulsar/BH binaries may allow the BH spin to be determined and the spacetime near the last stable orbit to be probed by lensing. These results will nicely complement iron-line spectroscopy of accretion disks that are also influenced by ray-path bending.

The State of the Art: Results on Binaries and Gravity. Timing observations on known pulsar binaries determine five of six Keplerian parameters [i.e. orbital period ($P_{\rm orb}$), projected semi-major axis ($a \sin i$), eccentricity (e), and the longitude (ω) and epoch of periastron (T)], with extremely high precision, better than 1 part in 10^{11} for T for the double pulsar J0737$-$3039 (Kramer et al. 2006). Post-Keplerian (PK) effects, including the advance of periastron ($\dot\omega$), orbital period derivative ($\dot P_{\rm orb}$), gravitational redshift (γ), and Shapiro delay (r, s), determine the two masses from any two of these effects and provide robust tests if GR is assumed. Different observables probe different aspects of gravity beyond the weak-field limit, including quasi-stationary vs. radiative aspects of the theories (Damour 2007). For the double pulsar the individual masses and consistency with GR are determined to better than 0.05%. Geodetic precession, a spin-orbit effect, alters the beaming geometry to produce pulse shape variations, occuring at rates of about 1 to 17 deg yr^{-1} in a few DNS binaries. While not as strong a test of GR (13% for the double pulsar; Breton et al. 2008), it has implications for the detectability of specific objects. Geodetic precession ~ 7 arc sec yr^{-1} has been measured with Gravity Probe B and is consistent with GR to about 1%.

Equivalence principles and alternative theories of gravity are assessed through a PK parameterization for arrival times that applies to any metric theory of gravity (Damour & Durelle 1986), combined with additional terms for some theories. Early measurements of orbital decay from the Hulse-Taylor binary PSR B1913+16 showed that several candidate theories had to be rejected (Weisberg & Taylor 1981). The Strong Equivalence Principle (SEP) holds in pulsar systems to about the same precision as lunar laser ranging for the Earth-Moon system (about 0.1%) and similarly for preferred-frame effects. Violations of local Lorentz invariance and conservation of momentum are limited by pulsar timing about 12 orders of magnitude better than from the perihelion shifts of Mercury and Earth. Dipolar gravitational radiation is predicted in tensor-scalar theories for NS-WD binaries because of the difference in grav-

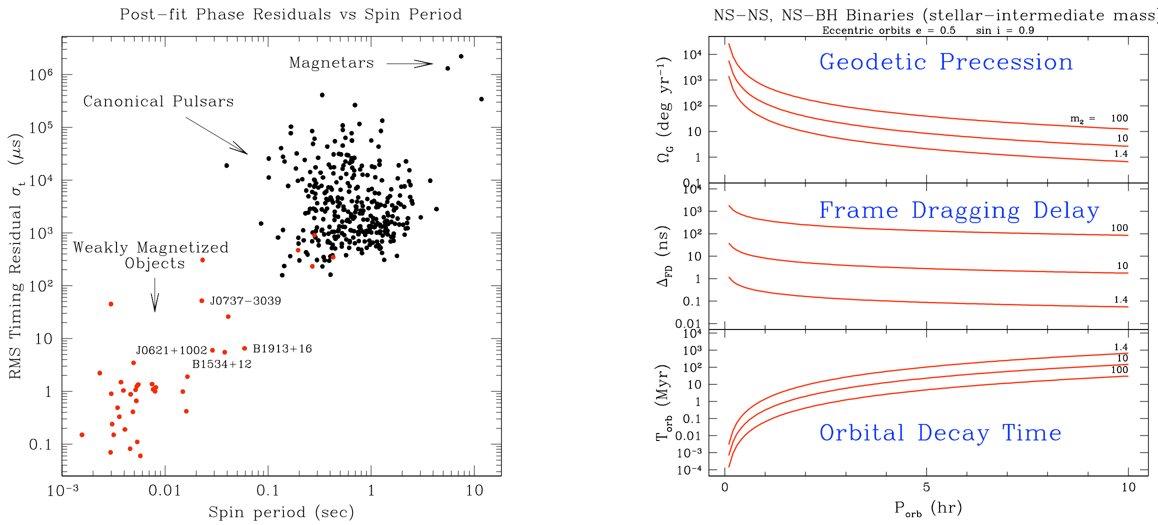

FIG. 1.— **Left: Timing Precision for Neutron Stars:** Scatter plot of rms timing residual vs spin period for the period range of rotating, non-accreting neutron stars, illustrating the smaller residuals for small spin periods and for lower magnetic fields; red points are for surface fields $B \leq 10^{10.7}$ Gauss. Canonical pulsar points are from Hobbs et al. (2004) while others come from specific references on timing of MSPs, DNS binaries, and magnetars. **Right: Long-term Orbital Effects in Relativistic Binaries:** The three panels show the geodetic precession rate, the frame-dragging delay, and the orbital lifetime due to gravitational wave emission from top to bottom, respectively. The three curves in each panel are for companion masses of 1.4, 10 and 100 $M_\odot$. An initial eccentricity of 0.5 is assumed and an orbital inclination $\sin i = 0.5$ has been used to calculate the frame-dragging delay.

itational binding energies. Dipole radiation increases the magnitude of the orbital period derivative. Careful assessment of $\dot{P}_{\rm orb}$ that accounts for contributions from Galactic acceleration and from geometrical changes by a pulsar's proper motion (Shklovskii effect) places strong limits of about 10^{-2} on the coupling constant of the scalar field. Changes in the gravitational constant would alter both the orbital period decay rate and the Chandrasekhar mass over cosmological time. Limits on both effects yield $dG/Gdt \lesssim 4 \times 10^{-12}$ yr^{-1}, comparable to results obtained with laser ranging to the Moon and Mars. Better precision measurements on more extreme binaries will have greater testing power by requiring that PK parameters be expressed to higher post-Newtonian order (Kramer et al 2006; Damour 2007). The strength of gravity in DNS binaries is 10 to 10^6 times stronger than in the solar system and can be arbitrarily stronger if self-field effects from dense NSs are important, as in some theories.

State of the Art: Timing Precision. The primary measurement is the time of arrival (TOA) of a pulse at a telescope. So far, the most precise measurements have been made in the radio band but pulsar timing is also an infrared through gamma-ray enterprise. A benchmark TOA precision (σ_t) is given by the pulse width W divided by the signal-to-noise ratio S/N, with added contributions from astrophysical and instrumental effects. Achieved precisions range from sub-microsecond for some millisecond pulsars (MSPs) to hundreds of milliseconds for magnetars. In some circumstances σ_t may be dominated by photon counts (in X- and gamma-rays), by processes within the pulsar magnetosphere and in the interstellar medium (radio), and by time-transfer uncertainties (all bands). The achievable TOA precision therefore has an intricate parameter landscape involving a combination of collecting area, detector noise, and astrophysical effects.

The spin stability of pulsars is another astrophysical factor that enables or limits their use as clocks for relativity. Spin fluctuations are wide in variety but often are manifested as red-noise processes. Some cases have bandpass power-spectral shapes suggestive of precession or some other complex interaction between the internal components of NS. The most stable objects are those with the fastest periods and the lowest spindown rates — the millisecond pulsars. Magnetars with large applied torques and rapid spindown rates are the noisiest. Figure 1 (left panel) shows the rms timing residual for the various pulsar classes. The plotted quantity includes results from heterogeneous data sets and different fitting procedures but is representative of salient trends. The best precision is achieved with low-magnetic field, *recycled* pulsars, which are exactly those found in most pulsar binaries.

Increasing the Testing Power for Theories of Gravity by Orders of Magnitude. It can safely be stated that the best opportunities using pulsar timing are yet to come. Boosting the testing power can come about from a combination of (a) improved timing and astrometric measurement techniques, (b) denser sampling by increasing the timing throughput of telescopes, (c) longer time baselines on individual objects, and (d) discovery of binary systems with larger-amplitude post-Keplerian and post-Newtonian effects.

Reconsidering the set of timing parameters (Keplerian, post-Keplerian and post-Newtonian), we note that some are associated with purely cyclical time dependences (e.g. a, ω, γ, r, s) while others, like the post-Keplerian parameters $\dot{\omega}$ and $\dot{P}_{\rm orb}$, produce secular terms that grow with time. For example, the apsidal angle $\omega = \omega_0 + \dot{\omega} t$ yields a linear perturbation $\Delta t \sim (a\dot{\omega}/c)t$, while the orbital period decay from GW emission yields a cumulative shift in the time of periastron $\Delta t \sim (\dot{P}_{\rm orb}/2P_{\rm orb})t^2$, that famously shows consistency with GR to better than 1% in the Hulse-Taylor binary, as summarized in Weisberg & Taylor (2005).

For cyclical terms, the amplitudes can be improved by improving the quality (σ_t) and the number (N) of arrival time measurements, yielding errors involving the factor $\sigma_t/\sqrt{N}$. Secular terms also improve according to this factor but they improve much more from the length of the timing program.

Some of the analyses require accurate distance estimates (D) made either from timing data or from separate interferometric parallax measurements. The timing parallax term scales as $\Delta t \sim ({\rm AU})^2/2cD \sim 1.2\ \mu s\ D^{-1}$ for D in kpc, becoming too small to measure for distant objects. Interferometric parallax measurements now reach the sub-milliarcsecond level and can be improved further. Parallaxes are crucial especially for those tests involving $\dot{P}_{\rm orb}$, which is contaminated by distance-dependent Galactic acceleration and Shklovskii effects.

Higher-order Timing Effects: Better timing precision and more extreme binaries (see below) will allow higher order effects to be measured, yielding stronger tests on theories of gravity. One effect is precession of the orbital plane in response to the geodetic spin precession, which in principle allows determination of the moment of inertia I of a pulsar (Damour & Schäfer 1988; Lattimer & Schutz 2005). The amplitude depends on geometry but is of order $1-10\ \mu s$ for currently known objects. Deriving I requires highly precise estimates for the spin-orbit and orbital inclination factors ($\sin\theta_{SO}$ and $\cos i$) using other relativistic terms, which has not yet been achieved but will be in the future. Determining the moment of inertia allows the radius of the NS to be determined, providing strong constraints on the equation of state, that complement nicely results obtained in X-ray observations of NS.

Frame dragging (Lense-Thirring precession), displays a cyclical term with very small amplitude $\sim 1\ ns$ for DNS binaries (Wex & Kopeikin 1999), that is currently undetectable as well as being degenerate with light-bending effects. However, pulsars orbiting high-mass, maximally spinning black holes in few-hour orbits will show discernable perturbations in the range of 1 μs for 100 $M_\odot$ BHs and $\sim$ 1 s for pulsars orbiting Sgr A*, the $4\times10^6\ M_\odot$ BH in the Galactic center, in one-day orbits. Detecting the spin allows the properties of a Kerr BH to be directly tested (e.g. Kramer et al. 2004).

Microlensing from stars will be detectable at the few μs level for pulsars viewed through the Galactic bulge over long time spans.

Finding Better Binaries: Post-Keplerian timing perturbations grow with increasing mass of the pulsar companion and most are also larger for shorter orbital periods or high eccentricity. Geodetic precession also grows rapidly with more massive, eccentric and faster systems. There exists now largely *un-mined binary search space* for finding new objects that yield timing effects that are one to two orders of magnitude larger than in known systems. The right-hand side of Figure 1 shows the geodetic precession rate, the delay from frame-dragging, and the orbital lifetime vs. $P_{\rm orb}$ for companion masses of 1, 10 and 100 $M_\odot$. The first two of these illustrate the great dividends to be gained by finding binaries with orbital periods less than one hour, say. Geodetic precession covers a full cycle or more over one year and frame dragging becomes larger than $\sim 1\ \mu s$ and thus within reach of measurement.

However, the same important timing effects in massive, compact binaries that make them important targets also make them difficult to detect, an explanation for why sub-hour binaries are not yet known. Fast binaries are selected against even in pulsar surveys that correct for orbital acceleration because pulse phase builds up too quickly over data spans of just a few minutes. Geodetic precession will likely cause the Hulse-Taylor binary to disappear for about 2/3 of its ~ 300 yr precession cycle starting in the near future. In faster systems, geodetic precession will cause pulsars to come and go on time scales that will require surveys to make multiple passes on the sky for this reason alone. The orbital period distribution scales as $dN/dP_{\rm orb} \propto P_{\rm orb}^{8/3}$ if systems are born at constant rate with identical initial periods. With a DNS birth rate in the Galaxy of about $10^{2\pm0.5}$ Myr^{-1} (based on four DNS systems; O'Shaughnessy et al. 2008), there should be 30 to 300 systems with one hour orbits or less and one system with a 10-min orbit. Such systems would truly be extraordinary physics laboratories and a significantly larger sample will elucidate the populations of short, hard gamma-ray bursts and chirped gravitational waves detectable with Advanced LIGO and its descendents. Detection of the fastest binaries requires high-order correction for orbital motion in a large parameter space. Figure 2 shows orbits of known DNS binaries with periods < 30 hr. In the right-hand panel, the orbital spiral-in and merger is shown along with the modest, secular increase in spin period of the recycled object in the system, demonstrating that recycled pulsars typically will remain observable throughout the merger process.

The Measurement Program: A *Galactic census* is needed to find pulsars in more extreme circumstances, including binary pulsars with sub-hour orbital periods, an array of millisecond pulsars for gravitational-wave detection, and objects relevant to other key questions not posed (e.g. high velocity pulsars as probes of kick mechanisms in supernovae). Next follows *precision timing campaigns* over several to many years with better arrival-time precision. Third is an *astrometry program* at ~ 0.1 milli-arcsecond to determine distances to pulsars and to reduce the number of unknowns in the timing analysis.

Galactic Census: Most NS originate from binary stars but themselves are predominantly solitary objects. Momentum kicks in supernovae evidently disrupt 99% of binaries. The 1% of NS that remain in binaries — particularly with NS and BH companions — are one of the primary target classes of the census along with spin-stable MSPs for nanohertz GW detection (see white paper by Demorest et al.). Figure 3 shows known and simulated pulsars projected onto the Galactic plane, with known DNS binaries designated to show that strong selection effects have limited their detection to our neighborhood of the Galaxy. This is also evident for pulsars of all types. The vast majority of the pulsars in the Galaxy beaming toward us have not yet been discovered, because surveys with existing facilities cannot go deep enough. A deep survey with a Square Kilometer Array (SKA) class instrument could detect the majority ($\sim 10^4$) of these pulsars, as shown in the figure.

Small periods (spin and orbital) and large system masses yield accumulated, non-linear phase terms that confound search algorithms that rely on strict periodicity of the pulsar signal. At present, only single-parameter acceleration searches are made. The next step is to search for full circular orbits. Pulsars in the Galactic center also require atypically high radio

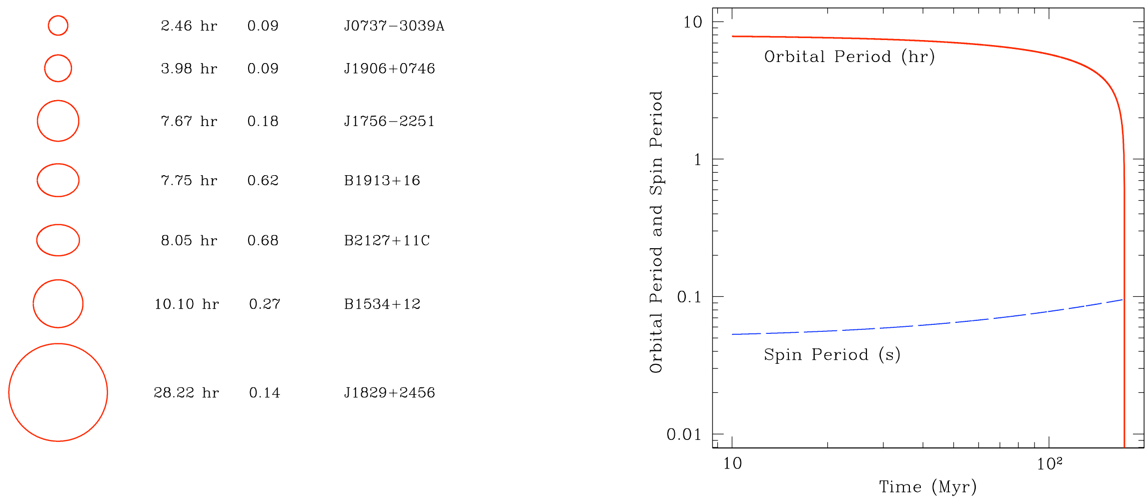

FIG. 2.— **Left: Orbits of Seven DNS Binaries:** Orbits are shown to scale for known double-NS binaries with orbital periods smaller than 30 hr. The orbital period and eccentricity are given along with the pulsar name. Those with orbital periods of 10 hr or less will merge on a time scale ~ 100 Myr, as demonstrated in the right-hand panel. **Right: Orbital Decay and Pulsar Spin Down:** The orbital and spin periods are illustrated for a double NS binary with initial orbital and spin periods of 8 hr and 50 ms, respectively. Such objects will merge before the pulsar emission shuts off, so they will remain detectable throughout the spiral-in process, except for gaps in visibility due to geodetic precession of the pulsar beam.

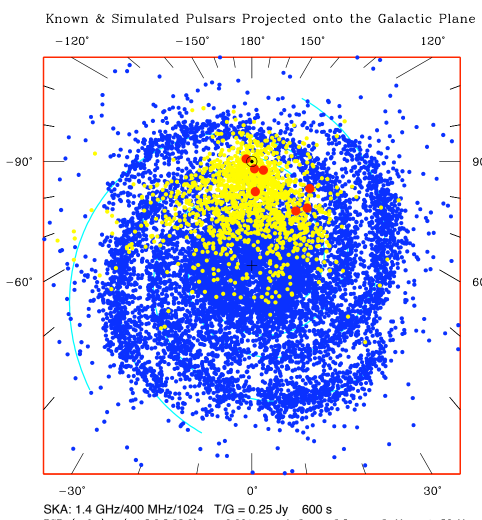

FIG. 3.— **Known and Discoverable Pulsars Projected onto the Galactic Plane:** The Galactic center and Sun are marked with '+' and $\odot$. Yellow points are known pulsars in the ATNF Pulsar Catalog. Red points show seven NS-NS binaries with $P_{\rm orb} < 30$ hr. Blue shows simulation points consistent with the known population that predicts $10 - 20 \times 10^3$ active radio pulsars are detectable with a full-Galaxy survey with the Square Kilometer Array at 1.4 GHz, taking into account selection effects, including radio-wave scattering (Cordes et al. 2004; Smits et al. 2009). Actual yields depend on the sky coverage of the SKA. The "reach" with current telescopes clearly excludes much of the Galaxy and/or luminosity function, so the vast majority of relativistic binaries remain to be detected, as well as millisecond pulsars required for gravitational wave detection.

frequencies ($\gtrsim 10$ GHz) owing to the intense plasma scattering that smears pulses.

Timing Program: Improvements in arrival-time precision are needed that can be achieved through a combination of new algorithms and larger timing throughput. The latter can be effected through the development of wide field-of-view telecopes that allow multi-tasked ("commensal") usage of telescopes.

The VLBI Astrometry Program: Pulsar VLBI has predominantly been done using dedicated arrays like the VLBA, reaching 5 kpc for one bright object (Chatterjee et al. 2009). As mentioned before, some gravity tests require removal of distance-dependent effects. Astrometry on more objects and to higher precision requires significant program time on telescopes larger than those in the VLBA, such as Arecibo, the GBT, the phased EVLA, and foreign telescopes, along with increases in processing bandwidth. Higher frequency VLBI (e.g.,

$5-8$ GHz), which is advantageous for removing ionospheric effects, will require a large boost in sensitivity provided by the SKA in order to reach most of the important pulsars. Future VLBI can resolve some pulsar binaries and provide transverse measurements that complement timing measurements, for a full 3D picture. These wide-orbit binaries are among those used in tests of the SEP.

Resources: Existing radio telescopes worldwide and high-energy satellites, such as the X-ray Timing Explorer and Fermi/GLAST are utilized near their capacity to search for new pulsars and time them. Long-baseline radio interferometry is now providing parallaxes of pulsars at distances up to ~ 5 kpc away. New telescopes are needed to enable all three major components of the science program with a particular need for greater sensitivity at centimeter wavelengths (1 to a few GHz) for pulsars in the Galactic disk and frequencies between 10 and 15 GHz to study pulsars in the Galactic Center. The increase in sensitivity can come about only incrementally with wider-bandwidth digital instrumentation; large improvements in lower-noise receivers are needed on existing, key telescopes (Arecibo, the GBT, and the VLA) and a dramatic increase in collecting area is needed in the southern hemisphere, including pre-SKA telescopes and the SKA itself.

Synergistic Spinoffs: The measurement program described here will have important byproducts for other enterprises, such as understanding magnetospheres of NS and beaming across the EM spectrum. The totality of pulsars will allow Galactic structure to be determined for extreme population I stars and will allow 3D modeling of the plasma density and magnetic field.

REFERENCES

Arzoumanian, Z. 2005, “Resolving Pulsar Binaries,” Future Directions in High Resolution Astronomy, 340, 303

Breton, R. P. et al. 2008,“Relativistic Spin Precession in the Double Pulsar,” Science,321,104

Chatterjee, S. et al. 2009, “Precision Astrometry with the VLBA: Parallaxes and Proper Motions for 14 Pulsars,” ApJ, in press (arXiv:0901.1436)

Cordes, J. M. et al. 2004, “Pulsars as tools for fundamental physics & astrophysics,” New Astronomy Review, 48, 1413

Damour, T. 2007, “Binary Systems as Test-beds of Gravity Theories,” arXiv:0704.0749

Damour, T. & Schäfer, G. 1988, “Higher-Order Relativistic Periastron Advances and Binary Pulsars,” Nuovo Cim., 101, 127

Damour, T. & Esposito-Farese, G. 1996 “Tensor-Scalar Gravity and Binary-pulsar Experiments,” PRL, 54, 1474.

Hobbs, G. 2004 “Long-term Timing Observations of 374 Pulsars” MNRAS, 353, 1311

Konacki, M., Wolszczan, A. & Stairs, I. H. 2003 “Geodetic Precession and Timing of the Relativistic Binary Pulsars PSR B1534+12 and PSR B1913+16” Apj, 589, 495

Kramer, M. et al. 2004 “Strong-field tests of gravity using pulsars and black holes,” New Astronomy Review, 48, 993

Kramer, M. et al. 2006 “Tests of GR from Timing the Double Pulsar,” Science, 314, 97

Lattimer, J. M & Schutz, B. F. 2005 “Constraining the Equation of State with Moment of Inertia Measurements,” ApJ, 629, 979

Smits, R. et al. 2009 “Pulsar Searches and Timing with the SKA” A&A, 493, 1161; also SKA Memo 105, http://www.skatelescope.org

Stairs, I. H. 2003,“Testing General Relativity with Pulsar Timing,” Living Rev. Relativity, 6

Weisberg, J. M. & Taylor, J. H. 1981 “Gravitational Radiation from an Orbiting Pulsar,” Gen. Relativ. Gravit., 13, 1

Weisberg, J. M. & Taylor, J. H. 2005 “The Relativistic Binary Pulsar B1913+16: Thirty Years of Observations and Analysis” in Binary Radio Pulsars, ASP Conf. Vol 238, 25

Wex, N. & Kopeikin, S. M. 1999 “Frame Dragging and Other Precessional Effects in Black-Hole Pulsar Binaries,” ApJ, 514, 388