TIMING OF MILLISECOND PULSARS

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Abstract.

Arrival times of some millisecond pulsars can be measured with sub-microsecond precision. This allows unprecedented measurements of the rotation of these stars, astrometric parameters including proper motion and parallax, motion in binary and complex dynamical systems, perturbations resulting from propagation through small scale turbulence in the interstellar plasma and other effects. In addition to the independent parameters which are required to model each pulsar, there is a set of global parameters that affect the array of pulsars in a correlated manner. These parameters involve the international atomic time scale, the ephemeris of the Earth's orbit and the gravitational wave background and have monopole, dipole and quadrupole and higher order angular signatures, respectively.

1. INTRODUCTION

Shortly after the discovery of the first millisecond pulsar, B1937+21, analysis of the arrival times of its pulses indicated that its rotation was extremely stable, $\frac{\Delta\Omega}{\Omega} < 10^{-13}$. The initial observations could be modeled by three rotational parameters – phase, rotation rate, and spindown rate – and two astrometric parameters – right ascension and declination. The measurement precision was unprecedented for pulsars – a few microseconds of time. This precision was the result of the high flux density, the short period and concomitant pulse width, and the unusually sharp structure of the average pulse profile. Pulse widths scale with the inverse square root of the period in simple polar cap emission models. The extreme stability of the millisecond pulsars allows their use for a variety of fundamental phys-

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ical and astrophysical investigations, and arises from the extremely large mechanical Q of these objects, $Q = \dot{P} \simeq 10^{-19}$ to 10^{-21}.

In this review I discuss first the *independent* parameters of each pulsar that are required to model pulse arrival time observations with the focus on millisecond pulsars and pulsars with companions. Next, I describe how these parameters provide information about the neutron star and, in some cases, the system in which it lives. For some pulsars, other areas of astrophysics can be explored with pulsar timing observations. In my final section I will discuss a number of applications that require a set of *global* parameters for a spatial array of millisecond pulsars. In brief these are: to stabilize atomic time; to tie ecliptic and equatorial reference frames together; to determine the masses of the outer planets; and to probe the cosmic background of gravitational radiation. Kaspi (1994) has reported on progress in millisecond pulsar timing, and Phinney & Kulkarni (1994) have recently reviewed other topics pertinent to millisecond and binary pulsars.

2. INDEPENDENT TIMING OF PULSARS

2.1. FORMULATION AND RECENT RESULTS FOR SINGLE PULSARS

Pulsar signals are faint. Large radio telescopes, wide bandwidths, and long integration times are required for precise pulsar timing. Use of large bandwidths is limited by the need to accurately remove the severe dispersion incurred as the signal traverses the interstellar plasma. A variety of solutions for dispersion removal and subsequent signal processing have been developed in recent years. The resulting data product is an average pulse profile whose first sample is time tagged using the observatory's atomic time scale. The epoch of arrival of a fiducial point on the average pulse is determined by a variety of software techniques. Pulsar timing precision is potentially limited either by the temporal stability of the intrinsic average pulse profile (Helfand *et al.* 1975; Weisberg *et al.* 1989; Cordes *et al.* 1990; Blaskiewicz 1993; Suleymanova & Shitov 1994) or by our ability to measure accurately the profile given calibration errors and strong polarization. The typical precision of these measurements is 0.01 to 0.001 periods. The topocentric pulse arrival time – a space-time event – is referred to an international atomic time scale (see below) using GPS time transfer techniques at most observatories. Pulsar timing proceeds with a number of arrival times per session on a given day, and a number of sessions per year. The analysis task outlined below is to generate a model for these many arrival times with no ambiguity of rotation number. Recent references on pulsar timing techniques include: Backer & Hellings (1986), Backer (1993), and Taylor (1992).

The observatory is a constantly accelerating laboratory. A relativistic space-time transformation of the observatory space-time reception event to the emission event in the pulsar's frame must be made to explore the link between the observed pulse arrival times and the rotational properties of the star. Pulsar emission is modeled as spherical waves emanating from a point source. The transformation can be broken into a relativistic clock term and spatial terms such as from the observatory to the Earth center and from the Earth center to the Solar System barycenter. Transformation from the Solar System barycenter to the pulsar cannot be done with any level of accuracy and therefore it is ignored. The scale of the different terms may be large or small with respect to the pulse period. For example, there are 640 982 pulses from B1937+21 stacked up across the Earth's orbit at any instant.

The pulsar's equatorial coordinates are required to remove these effects. Iteration is required in the process of determining pulsar rotation and astrometric parameters. The phase residuals are used to solve for new parameter estimates. Typically one solves for phase, frequency, frequency first derivative, right ascension and declination. With long data sets and high precision timing one can solve for proper motion components (e.g., Nice & Taylor 1994) and even parallax (Ryba & Taylor 1991; Camilo *et al.* 1994). Proper motions and parallaxes provide fundamental data for discussions of the origin and evolution of the millisecond pulsar population. The proper motions of pulsars in globular clusters, which are just now being determined, can be combined with their Doppler velocities to discuss cluster evolution and the mass distribution in the galaxy.

While one cannot model the free space propagation of the pulsar signal, one must model the dispersive delay through the cold, interstellar plasma. This is reasonably straightforward owing to the simple dependence of group velocity on frequency. Measurements at two radio frequencies spaced by an octave provide differential arrival times that yield the required column density of electrons needed to extrapolate the arrival time to infinite frequency. Often alignment of the fiducial point between frequencies is confounded by spectral index variations across the pulse profile and by instrumental effects (e.g., Foster *et al.* 1991). Measurements at three or more radio frequencies are recommended.

The interstellar plasma is turbulent on a wide range of length scales. For the highest timing precision the electron column density must be monitored (Phillips & Wolszczan 1992; Backer *et al.* 1993a; Kaspi *et al.* 1994). The uneven electron density distribution leads to refractive and diffractive effects that further complicate the removal of plasma propagation effects (Foster & Cordes 1990; Hu *et al.* 1991). Fig. 1 illustrates a 4.5 year record of refractive flux density variations and dispersion measure changes for B1937+21.

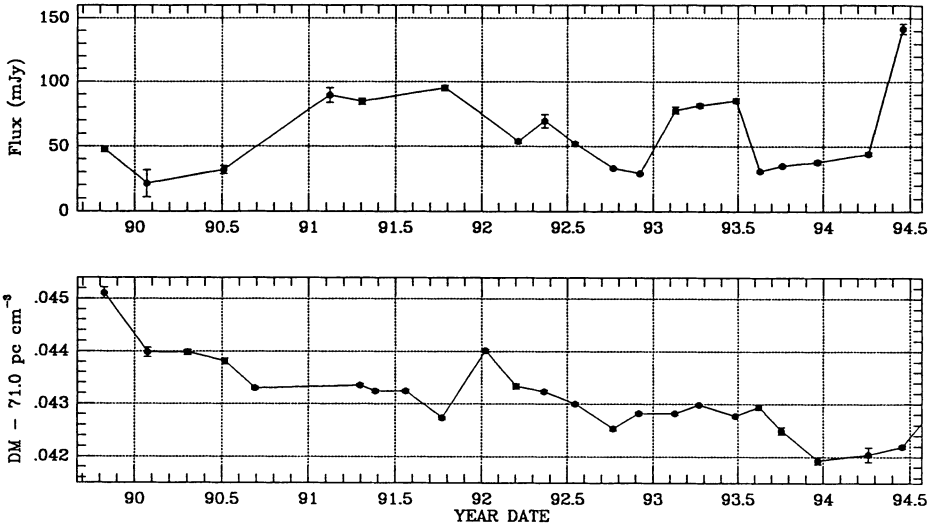

Figure 1. Flux density at 800 MHz (a) and dispersion measure (b) of B1937+21 as a function of time from the pulsar timing array experiment at NRAO Green Bank. For experimental details see Backer *et al.* (1993a). On these long time scales there is not a strong correlation between variations of the two quantities.

Cordes *et al.* (1986), Blandford *et al.* (1985) and others discussed the expected relationships between scintillation amplitude, dispersion measure variations and pulse arrival times for turbulence with various logarithmic slopes. Lestrade (1994) has demonstrated a correlation between scintillation amplitude and pulse arrival time for PSR 1937+21 on short time scales. There is now evidence for propagation events that are attributed to traversal of a caustic caused by discrete interstellar plasma lenses (Cognard *et al.* 1993). Precise timing through these events may be possible with dense sampling in time at a number of frequencies although the simplest approach would be to observe at sufficiently high frequency where the amplitude of such effects is reduced below measurement error. While these effects are a nuisance to precision pulsar clock experiments, they do provide crucial constraints on the nature and distribution of this turbulence.

A second, frequency independent, 'propagation' effect occurs as the signals pass through the distorted space-time metric in the vicinity of a massive body (Shapiro 1964). This delay is the *longitudinal* counterpart of the more familiar bending of light which is a *transverse* effect. The time variable Shapiro delay through the Solar System is removed by simple calculation using a PPN GR parameter that is adequately determined by radar and VLBI experiments. Delays from the passage by stars along the line of sight are large, but only slowly varying.

The primary rotation parameters – phase, frequency, and frequency derivative – are sufficient to model most millisecond pulsars. The ratio of frequency and frequency derivative provide a time scale for the evolution of the pulsar's rotational energy. The age of the pulsar can be estimated from this ratio, if one assumes both that the slowing down follows the simple vacuum dipole radiation formula and that the initial rotation frequency is much larger than the present one. These assumptions may be questioned for the millisecond pulsars. In particular, the initial period of the shortest period objects may be comparable to the present period. An additional uncertainty arises in that galactic motion – transverse velocity and acceleration – give rise to significant contributions to the frequency derivative (Camilo *et al.* 1994). Pulsars in globular clusters will have an additional source of acceleration owing to the combined effects of nearest neighbor stars and the smooth, deep central potential (Anderson *et al.* 1990).

In the past few years the millisecond pulsars which have the longest record of timing have shown signs of *instability* at the level of a few microseconds for B1937+21 (Kaspi *et al.* 1994) and B1821–24 (Cognard *et al.* 1994) over time scales of several years. Fig. 2 displays our data which also shows the instability of B1821–24 arrival times along with the record of dispersion measure variations. The contribution of atomic time scale and ephemeris uncertainties to this are discussed further below. The conclusion is that these instabilities are internal to the pulsars. While solid state physicists have proposed detailed models of sudden glitches in the otherwise smooth rotation of pulsars, there is not a good understanding of the origins of the $1/f$-like spectrum of noise. All forms of internal timing noise are driven by figure readjustment forces that increase monotonically with $\dot{\Omega}$. The noise for millisecond pulsars with low $\dot{\Omega}$'s is expected to be small, but not zero. The dependence of timing noise on $\dot{\Omega}$ reaching to millisecond periods has been discussed by Dewey & Cordes (1989) and more recently by Arzoumanian *et al.* (1994a).

2.2. PULSARS WITH COMPANIONS

Pulsar companions add complexity for timing measurements in that an additional transformation must be done from the system barycenter to the pulsar. Initial analysis using the apparent rotation frequency to follow the Doppler curve as in a single-line spectroscopic binary is often required for millisecond pulsars whose period may be much smaller than the orbit size. Five parameters are required to model the general Keplerian binary system. The orbit size projected along the line of sight, the orbital period, and an epoch when the star passes through the plane of the sky are needed for all systems. If the orbit is eccentric, then the eccentricity and the orientation

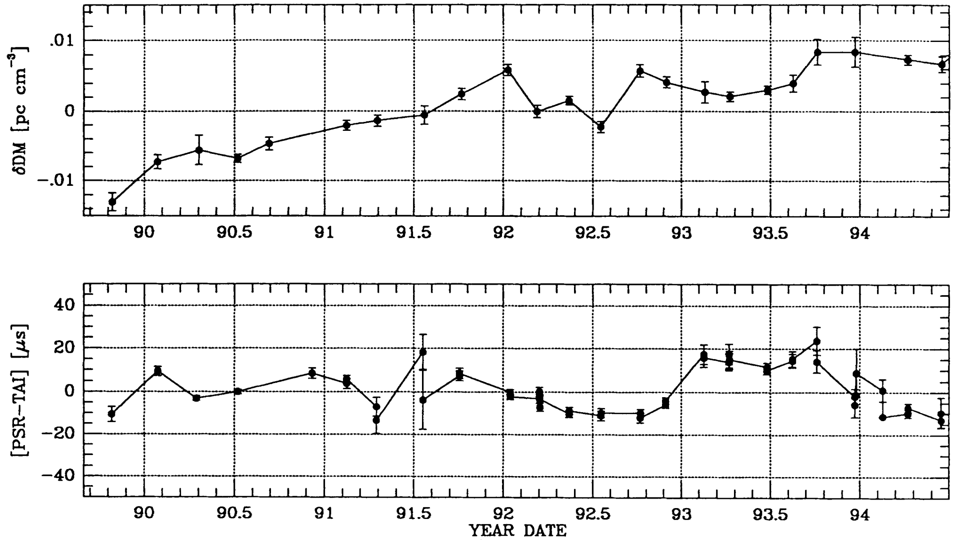

Figure 2. Temporal variations of the dispersion measure (a) and the arrival time (b) of B1821–24. The timing model includes pulse phase, frequency, frequency first derivative, right ascension, declination and proper motion in right ascension. The timing of B1821–24 is not sensitive to declination proper motion. A constant dispersion measure of 119.8 pc cm^{-3} has been removed.

of the periastron point with respect to the line of nodes are required.

B1620–26 is an 11-ms period pulsar with a 0.3 $M_\odot$ companion in a 191-d orbit that is located in the nearby globular cluster M4 (Lyne *et al.* 1988). Timing observations following its discovery were not stable until the presence of a large frequency second derivative was added to the model. The large value of $\ddot{\Omega}$ is best explained by the secular influence of a second bound companion with an orbital period of 100's of years (e.g., Backer *et al.* 1993b; Thorsett *et al.* 1993a). The principal observed effect in our seven-year data set is then an acceleration derivative of the center of mass frame of the 191-d binary system which produces the apparent frequency second derivative. Fig. 3 displays residuals from a recent fit to the data that shows the effects of a third derivative of the rotation frequency as a quartic timing residual. This provides a measure of the component of the acceleration second derivative which is estimated as 3.3 10^{-24} cm s^{-2}. The formation and stability of this system are under considerable debate (Sigurdsson 1993; Rasio 1994). Like other pulsars in globular clusters B1620–26 is providing a new window into dynamical processes that contribute to the stability of clusters against gravitational collapse (Phinney 1992). Confirmation of this hypothesis for B1620–26 will eventually come from long duration timing observations. A tentative identification of the optical counterpart has been

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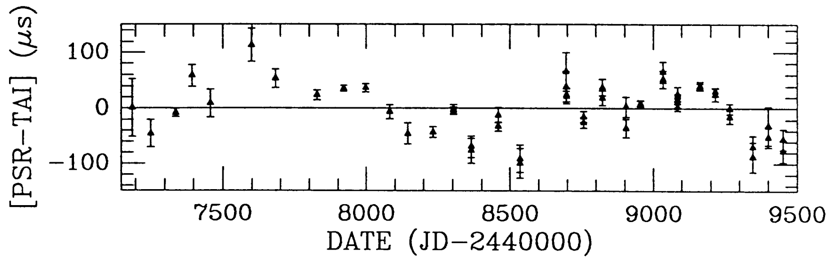

Figure 3. **Timing residuals for pulsar B1620–26 which has two companions in hierarchical orbits and resides in the globular cluster M4. The model removed has parameters of phase, frequency, frequency first derivative, frequency second derivative, right ascension, declination and right ascension proper motion.**

made (Bailyn *et al.* 1994), and followup HST observations have been proposed. If the orbital planes of the two companions are not collinear, the projected orbit size will change secularly. Current data analysis is beginning to show this effect, but the significance is not high (Backer & Thorsett 1994).

An entirely different, multiple companion system is found in B1257+12 as reported by Wolszczan (1994; these proceedings). This pulsar with planets is unique amongst the well studied millisecond pulsars. Yet another subclass of millisecond pulsars are objects like B1957+20 whose companion produces an eclipse during inferior conjunction (Fruchter *et al.* 1990). The companions have masses intermediate between those in low mass binary systems like B1620–26 and the planets in B1257+12. High precision timing of B1957+20 has revealed secular variations of the orbital period (Arzoumanian *et al.* 1994b) that provides important constraints on the physical state of the companion star.

A number of post Keplerian parameters are required to explain the relativistic effects of gravity. These are observable when the effects are large owing to the combined effects of a high eccentricity, a short orbital period, a high mass companion, a strong pulsar, and/or a large telescope with sensitive electronics. Briefly the effects are: precession of periastron as in Einstein's test for Mercury's orbit; relativistic clock correction which results from transverse Doppler effect and gravitational redshift; the Shapiro delay; and the decay of the orbit owing to the back reaction from radiation of gravitational waves. Some of the latest results including the first tests of strong field effects in General Relativity are described by Taylor *et al.* (1992). Apart from the fundamental test of physical theory provided by these observations, one also obtains accurate values for neutron star masses (Thorsett *et al.* 1993b).

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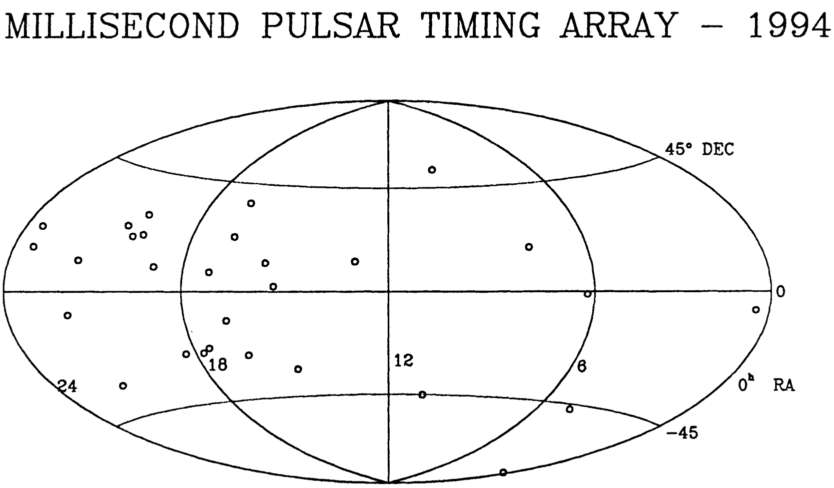

Figure 4. **Millisecond pulsar timing array plotted in equatorial coordinates. Pulsars included have periods less than 15 ms. The non-uniformity in distribution reflects a combination of search completeness and true galactic distribution. Owing to large differences in flux density and pulse profile morphology different pulsars can be timed to different levels of precision.**

3. GLOBAL TIMING OF PULSARS

In the previous section the timing of isolated and binary pulsars was discussed. The data for each pulsar were treated independently using a model of the Earth's space-time coordinate as a function of epoch that is assumed to be more accurate than the precision of the pulsar data. In this section the limits of this model are discussed, and the influence of a stochastic background of gravitational radiation on pulsar arrival times is presented. The section concludes with a description of the use of an array of precisely timed pulsars to solve for *global* parameters that affect all objects in a correlated manner. Fig. 4 displays the current array of millisecond pulsars.

3.1. TIME AND TIME TRANSFER

The definition of the second of Terrestrial Time (TT) is 9 192 631 770 cycles of the frequency corresponding to a fine structure transition in the ground state of the Cesium 133 atom at sea level on the geoid. An initial epoch is required to define a time scale. TT replaces International Atomic Time, TAI. The atomic standards laboratories – in Washington, Boulder, Paris, Braunschweig, Tokyo – realize this scale. The time scale required for pulsar timing is that of a clock at rest in the solar system barycenter inertial reference frame: Barycentric Coordinate Time (TCB). These definitions and their impact on pulsar timing are discussed by Guinot & Petit (1991), Seidelmann & Fukishima (1992), and Fukishima (1994). The epoch when atomic time reads some value, such as zero or 2440000.0 days 0 seconds, is not of particular concern here. Accurate realization of this definition is made difficult by the fact that Cesium clocks are affected by temperature, magnetic fields, vibrations of the room, interactions with container walls, and so on. Many of these effects can shift the frequency and will vary with time.

Estimates of the stability of TT on yearly time scales are difficult to obtain owing to its inclusion of all of the world's standards in its definition. Estimates by Guinot and Petit suggest that the stability is just under 10^{-14}. On longer time scales there is even less understanding of the stability other than the statements that the standards have been improving on a time scale shorter than a decade and that the stability slowly degrades with time interval from its minimum value on time intervals of about six months. The most precise pulsar timing is now sensitive to choice of atomic time scale (Kaspi *et al.* 1994).

Timing of an array of millisecond pulsars can provide independent information to help stabilize TT on intervals of years to decades. Time scale errors will have a monopole signature as one moves around the sky – all pulsars will arrive early or late in a correlated manner. Creation of a pulsar time scale then requires defining, in the simplest case, their initial epochs, frequencies, frequency derivatives, and equatorial positions which is just five parameters. As already discussed, further parameters are required and, in addition, the most closely studied millisecond pulsars show signs of instability in the rotation rates. The prospects of creating a pulsar time scale are not clear.

Pulsar timing observations are conducted at remote observatories. While today transfer of a time scale from the standards laboratories to the observatories is straightforward using GPS, care needs to be taken to ensure that the remarkable *short* term time transfer stability inherent in the GPS technique is maintained to ensure *long* term stability. Changes in the measurement technique within the observatory and the location of GPS receivers need careful calibration to ensure stability over decades.

3.2. EPHEMERIS AND FRAME TIE

The transformation from the observatory to the solar system barycenter inertial reference frame requires a precalculated ephemeris of the earth's motion. The ephemeris is constructed from a detailed model of solar system dynamics that includes the Sun, all planetary systems, minor planets, and a band of matter representing the asteroid belt, and uses an appropriate level of relativistic effects (Standish 1990a). Table 1 gives the current estimates of the errors in planetary masses, and the corresponding offset between the estimated barycenter location and the "true" location. These mass errors are large with respect to asteroid and cometary masses, but comparable to masses of the largest minor planets and larger moons. The barycenter will also be shifted by errors in the celestial coordinates of the planets.

TABLE 1. Planetary Mass Errors

System	Δm_{p} (10^{22} gm)	P_{p} (y)	r_{p} (AU)	$\Delta r/c$ (ns)	Reference
Mercury	1.4	0.25	0.39	1	Mariner
Venus	1.5	0.62	0.72	3	Mariner
Mars	0.2	1.88	1.52	1	Mariner
Jupiter	150	11.9	5.20	1950	Voyager
Saturn	300	29.5	9.52	7140	Voyager
Uranus	15	84.0	19.2	720	Voyager
Neptune	30	165	30.0	2250	Voyager

The arrival time transformation is effected by a scalar product between the observatory vector, which is of order 500 s – the AU – in length, and a unit vector in the direction of the source. This means that the planetary timing error for pulsar j in direction $\hat{\mathbf{n}}_{\mathbf{j}}$ will be

$$c\Delta t_{pj}(t) = \Sigma_p[\left(\frac{\Delta m_p}{\mathrm{M}_\odot}\right)\mathbf{r_p(t)} + \left(\frac{m_p}{\mathrm{M}_\odot}\right)\mathbf{\Delta r_p(t)}]\cdot\hat{\mathbf{n}}_{\mathbf{j}},$$

where Δm_p, $\mathbf{r_p}$, and $\mathbf{\Delta r_p}$ are the mass error (Standish 1990b), position, and position error (Standish 1990c), respectively, of planet p.

At any instant the residuals for different pulsars will differ as a result of the dot product in the above expression. There will be a slow variation around the sky with a dipole signature in the residuals. The temporal signature will be a cubic phase residual on short time scales, and periodic on time scales exceeding those of the periods of the outer planets. Kaspi *et al.* (1994) have demonstrated by timing two nearby pulsars over an 8-year span that ephemeris errors are not important yet at the several microsecond level.

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3.3. GRAVITATIONAL WAVE BACKGROUND

Precise pulsar timing may allow direct detection of long-wavelength gravitational radiation. Gravitational radiation is a perturbation of the spatial part of the space-time metric. One can view this perturbation as a change in the index of refraction from unity for propagation of an electromagnetic wave in simple three dimensional, Cartesian space. The transmission time from emission to reception then varies according to the integration of the metric perturbations along the path. The perturbation of the transmission time from the simple geometric path L/c varies with time as the radiation traverses the line of sight. The integration produces contributions at both the Solar System and pulsar ends from incomplete cycles of each spectral component of the gravitational radiation. The local contribution will lead to a correlation between timing residuals around the pulsar timing array with quadrupole and higher order angular signatures. The pulsar end contributions will have equal amplitudes and will be uncorrelated. For a general background of gravitational radiation the correlated component can be represented by independent waves along orthogonal axes with five independent parameters (Hellings 1990). The correlations can be displayed as apparent Doppler shift patterns using the formulation developed by Detweiler (1979). These patterns may be used as a basis of functions for analysis of pulsar timing array data (Backer 1993). Doppler shifts are derived from the temporal derivative of timing residuals. Fig. 5 displays one of the five Doppler patterns and demonstrates the quadrupole and higher order angular structure that allows gravitational radiation effects to be detected in the presence of time (monopole) and ephemeris (dipole) perturbations. The Doppler shifts themselves are not measurable owing to the period fitting done for each pulsar. Detection requires temporal modulations of each Doppler pattern with a spectrum of fluctuations. The amplitude and shape of these spectra will be the primary information to relate to source models.

A number of sources of long-wavelength gravitational background radiation have been proposed in the past decade. Defects in the space-time continuum called cosmic strings were once proposed as the gravitational centers that produced the large-scale structure we see today in the distribution of galaxies (Vilenkin 1981). The principal channel for decay of these strings is gravitational radiation with a spectrum extending from inverse months to inverse centuries (Romani 1988; Bennett & Bouchet 1991; Caldwell & Allen 1992). The millisecond pulsar timing observations by Kaspi *et al.* (1994) place strong constraints on this theory. Strings could exist and decay at a level lower than that required for structure formation. Detweiler (1979) proposed that precision pulsar observations might detect the slow decay of massive binary black holes in distant quasars and AGNs. Ra-

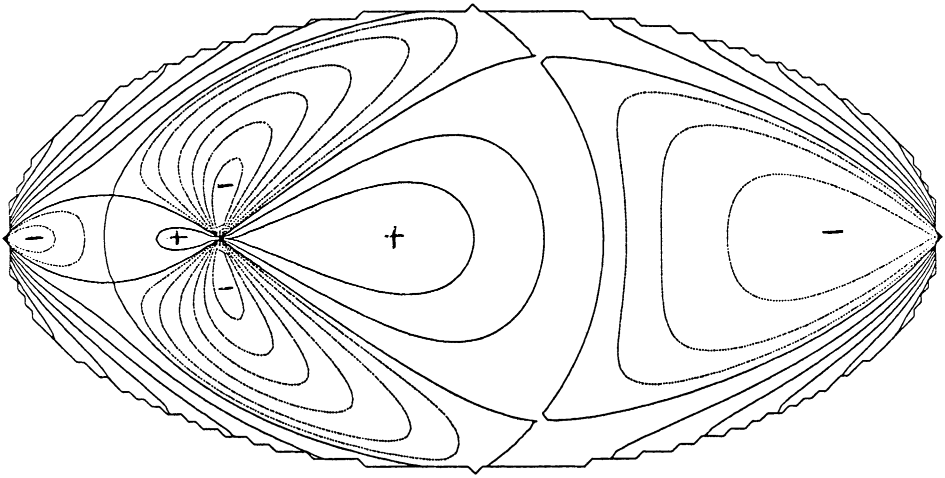

Figure 5. **Angular Doppler pattern on the celestial sphere for one independent component of a background of gravitational radiation. Timing residuals of the array of pulsars shown in Fig. 4 would show correlations with these Doppler patterns modulated by a temporal fluctuation spectrum.**

jagopal & Romani (1994) have taken a new look at this with estimates of the level of the spectrum over a range of interesting frequencies. Attempts at direct detection of the gravitational radiation background spectrum are important even without a proposed source based solely on serendipity.

3.4. PULSAR TIMING ARRAY EXPERIMENTS

There are a number of pulsar timing array programs underway at major radio observatories around the globe. Any regular monitoring of the strong, millisecond pulsars will contribute to the general data base for global analyses discussed in the previous section. The programs include those at Jodrell Bank in England, Nançay in France, Effelsberg in Germany, Parkes in Australia, Usada in Japan, Green Bank, WV in USA and Arecibo in USA. At a number of these observatories more than one group of investigators are conducting regular timing.

At the NRAO Green Bank site our group initiated a pulsar timing array experiment with the 42m telescope in 1987. Our first results are described in Foster & Backer (1990). The observations are conducted every two months at 800 and 1400 MHz. The two frequencies allow removal of time variable dispersion (Backer *et al.* 1993a). This year we introduced new hardware that will allow higher precision measurements, began sampling a significantly larger set of objects (Table 2), and initiated observations with a 26m 'pulsar monitoring telescope'. We look forward to the commissioning

TABLE 2. Pulsar Timing Array - NRAO Green Bank

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             1987  1988  1989  1990  1991  1992  1993  1994
            +-----+-----+-----+-----+-----+-----+-----+-----+
B1821-24    |    |------------------------------------------
  3.1 ms    |
B1937+21    |    |-----------------------------------------=
  1.6       |
B1620-26    |      |----------------------------------------
 11.1       |
B1855+09    |                |------------------------------
  5.6       |
B1257+12    |                     |-------------------------
  6.2       |
J1713+0747  |                                |--------------
  4.6       |
J2317+1439  |                                      |--------
  3.4       |
J2145-0750  |                                         |-----
 16.1       |
J0034-0534  |                                         |-----
  1.9       |
J0613-0200  |                                            |--
  3.1       |
J1730-2304  |                                            |--
  8.1       |
J0437-4715  |                                             |-
  5.8       |
            +-----+-----+-----+-----+-----+-----+-----+-----+
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of the 100m Green Bank Telescope (GBT) in 1996. The goal is to have timing residuals at or below one microsecond for a modest number of pulsars distributed across the full sky accessible to Green Bank.

4. OUTLOOK

The precise timing of millisecond pulsars has a bright future. New surveys continually find new objects that are independently interesting and augment the pulsar timing array discussed above. New instrumentation is being developed both to search for pulsars with even shorter rotation periods and to investigate known objects with higher precision. Telescopes such as those at Arecibo, Nançay and Westerbork are being refurbished to provide new capabilities for pulsar research. Telescopes such as the GMRT and the GBT which are under construction will be important for pulsar timing and related measurements. A number of propagation phenomena affect pulsar arrival times on short times scales, days to weeks. The time is ripe for a dedicated pulsar monitoring telescope, and some efforts toward this with a 26m antenna are underway. A larger aperture is, of course, important given the weakness of most pulsar signals. Finally radio astronomers are considering the idea of a radio telescope with a square km of collecting area. This would provide spectacular sensitivity for pulsar research at microwave frequencies.

The next decade will then bring: new insights into the origin and evolution of millisecond pulsars; an assessment of the maximum rotation rate of neutron stars; further tests of relativistic gravity including further new constraints on strong field effects; a clearer picture of the distribution and spectrum of interstellar plasma microturbulence; an understanding of the discrete structures in the interstellar plasma; a programmatic link between Terrestrial Time scale and that established by the pulsar timing array; improved masses of the outer planets; an improved tie between the celestial and ecliptic reference frames; and a detection of, or improved limits on, the background of gravitational radiation.

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