RXTE Absolute Timing Results for the Pulsars B1821−24 and B1509−58

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ABSTRACT

Observations with the Rossi X-ray Timing Explorer and the Jodrell Bank, Parkes, and Green Bank telescopes have enabled us to determine the time delay between radio and X-ray pulses in the two isolated pulsars B1821−24 and B1509−58. For the former
we find that the narrow X-ray and radio pulse components are close to being coincident in time, with the radio peak leading by 0.02 period ($60 \pm 20 \mu s$), while the wide X-ray pulse component lags the last of the two wider radio components by about 0.08 period. For the latter pulsar we find, using the standard value for the dispersion measure, that the X-ray pulse lags the radio by about 0.27 period, with no evidence for any energy-dependence in the range 2-100 keV. However, uncertainties in the history of the dispersion measure for this pulsar make a comparison with previous results difficult. It is clear that there are no perceptable variations in either the lag or the dispersion measure at time scales of a year or less.

Subject headings: instrumentation: miscellaneous, pulsars: individual (PSR B1509−58, PSR B1821−24), radiocontinuum: stars, X-rays: stars

1. Introduction

In the past, various attempts at absolute timing of pulsar signals have been made, trying to establish the phase lag between radio and X-ray pulses. Examples include the papers on PSR B1509−58 by Kawai et al. (1991) and Ulmer et al. (1993). From these we know that there is a phase lag and that it is, roughly speaking, between 0.25 and 0.35. First, Buccheri et al. (1978) and, more recently, Kanbach et al. (1994) have measured the phase lag between gamma-ray and radio emission for the Vela pulsar. Masnou et al. (1994) reported for the Crab pulsar that the radio pulse appears to lag the gamma-ray pulse by about 0.5 ms, based on Figaro II observations. This was not confirmed by the CGRO observations of Nolan et al. (1993) and Ulmer et al. (1994) (respectively, EGRET and OSSE data), though the former did not comment on the issue. The latter find the phase lag to be less than 30 $\mu s$, but with an uncertainty of 300 $\mu s$. Hence, we feel that it is fair to say that in the case of the Crab pulsar, for most past high energy astrophysics space missions, the lag may be considered zero for all practical purposes because of uncertainties in absolute time keeping. If there is a lag, it has to be significantly less than 1 ms.

This situation is different for the Rossi X-ray Timing Explorer (RXTE or XTE) when using one or both of its main instruments, the Proportional Counter Array (PCA) and the High-Energy X-ray Timing Experiment (HEXTE). The precision and accuracy of the RXTE absolute timing will, in principle, allow measuring phase lags as short as 10 $\mu s$. This means that for all known X-ray pulsars the X-ray time keeping will no longer be the dominant source of uncertainty. However, in most, if not all, cases we will not be able to achieve an accuracy of 10 $\mu s$ since we will be limited by the accuracy of the radio observations, the differing shapes of the light curves (as well as variations therein depending on waveband and time), and counting statistics.

This type of measurement provides important information for a better understanding of the emission processes involved. In isolated neutron stars, powered by spin-down rather than accretion,
the pulsed emission is likely to originate from either a polar cap (Daugherty and Harding 1982) or synchrotron processes in the outer magnetospheric gaps (Cheng, Ho, and Ruderman 1986). For more quantitative treatment of the latter type of models see, e.g., Smith (1986), Romani and Yadigaroglu (1995). Accurate absolute timing data will increase our knowledge of the precise location where the emission originates and of the geometry of the magnetic field lines.

This paper presents absolute timing results for two stable radio pulsars, PSR B1821−24 and PSR B1509−58, using RXTE and the Jodrell Bank, Parkes, and Green Bank radio telescopes. For the former pulsar we will also make a comparison with ASCA observations. Together with similar results for the Crab pulsar (PSR B0531+21) which are described in a separate paper (Rots et al. 1998), the experiment demonstrates the capabilities of the RXTE in this area. In addition to the scientific results, it is our intention to provide with this paper a reference for RXTE absolute timing issues.

2. RXTE Timing Accuracy

The RXTE Mission Operations Center (MOC) performs about ten calibration observations of the spacecraft clock per day. The calibration, using the USCCS (NASA/GSFC 1991) technique, relies on a round trip signal, tagged by the spacecraft clock’s time stamp, to determine the spacecraft clock offset. The method claims to provide absolute time with an accuracy of 5 µs. Parabolic fits to datasets extending over periods of about a week show deviations of no more than 1 µs which is consistent with quoted uncertainties for the various steps in the procedure. However, the true uncertainty is dominated by the clock at the ground station at White Sands which is only “required to agree with UTC at the Naval Observatory to within 5000 ns (5 µs)”, though it “is typically kept within […] 2 µs of UTC” (NASA/GSFC 1991). Consequently, we shall assume that RXTE absolute time is correct to within 5 µs. In addition, however, most of the data used in the course of this investigation suffer from a slight additional degradation, leading us to adopt a value of 8 µs for the uncertainty in absolute time for observations made before April 29, 1997 (MJD 50567). This degradation was caused by a known error in the clock calibration ground software which was corrected on that date.

We have validated these calibrations by astronomical observations of burst source 1744−28 (comparing CGRO-BATSE and RXTE-PCA data) and the pulsars PSR B1509−58 (period 150 ms) and PSR B0531+21 (Crab, period 33 ms) to an accuracy of 1 ms. Beyond that level of accuracy, uncertainties in the knowledge of the properties of the celestial objects preclude further validation. However, the validation justifies, in our minds, accepting the MOC’s calibration results.

All XTE data items are tagged with a time stamp taken from the spacecraft clock, with a maximum resolution of 1 µs for PCA data, 8 µs for HEXTE data. Measurements of timing delays internal in the spacecraft were made before launch, using a muon source. These measurements
compared the true time of the events with the time tags attached by the instrument data systems and hence include detector, as well as data system, delays. The timing delay for PCA events was determined to range from 16 \( \mu \text{s} \) for most events to 20 \( \mu \text{s} \) at low pulse heights which is close to expected values. The delay is the sum of all analog processing and transfer times, and the time tag is applied by the Experiment Data System (EDS). The HEXTE time stamp, on the other hand, is applied by the HEXTE Data System at the moment the lower level discriminator is exceeded; the resulting HEXTE instrumental delay is less than 1 \( \mu \text{s} \).

The time, as recorded in RXTE FITS files is TT (Terrestrial Time), with an accuracy of better than 100 \( \mu \text{s} \). Additional corrections, based on the MOC’s calibrations can reduce the error to 8 \( \mu \text{s} \). The issue of time systems is dealt with in more detail in the RXTE-GOF WWW pages\(^4\) (see: “Time Tutorial”\(^5\) and “Absolute Time Calibration”\(^6\)), and in full detail by Seidelmann et al.\(^6\) (1992).

All other sources of timing error that affect barycenter corrections, are small compared to the clock uncertainties quoted above. The 3\( \sigma \) errors for the solar system ephemeris and the RXTE orbit ephemeris are 0.1 \( \mu \text{s} \) and 0.25 \( \mu \text{s} \), respectively. In summary, RXTE time stamps, with and without barycenter correction, can be corrected to within 5 \( \mu \text{s} \) (8 \( \mu \text{s} \) before MJD 50567) of absolute time. We adopted corrections for the instrumental delays of 16 \( \mu \text{s} \) and 1 \( \mu \text{s} \) for PCA and HEXTE, respectively.

In this paper we present absolute timing results for two stable radio pulsars, PSR B1821–24 and PSR B1509–58. We do not include our extremely high signal-to-noise observations of the Crab pulsar here; interpretation of those data requires a careful treatment of the intrinsic timing noise in that source, and will be reported separately (Rots et al. 1998).

3. Analysis of RXTE Observations

We report here on observations made with the two main instruments on RXTE. The Proportional Counter Array (PCA) consists of five Xenon-filled detectors that cover the energy range 2-50 keV with a combined nominal collecting area of 7000 cm\(^2\). The High-Energy X-ray Timing Experiment (HEXTE) consists of two clusters of four NaI/CsI “phoswich” scintillation detectors which are usually rocking to provide a background estimate through a beam switching technique; the combined nominal collecting area is 800 cm\(^2\) per cluster. Since we are interested in pulsed signals, we switched off the rocking.

Public RXTE observations of PSR B1821–24 were made on September 16, 1996 (MJD 50342)

\(^4\)http://rxte.gsfc.nasa.gov
\(^5\)http://heasarc.gsfc.nasa.gov/docs/xte/abc/time_tutorial.html
\(^6\)http://heasarc.gsfc.nasa.gov/docs/xte/abc/time.html
in the context of an RXTE-ASCA clock cross-calibration project. The total RXTE exposure time was 6559 s, divided over two orbits. The PCA data configuration used was *GoodXenon* which records all good events detected in the Xenon chamber with full timing accuracy of 1 µs. To improve the signal-to-noise ratio, we only used the photons detected in the top Xenon layer. The pulsed signal is too weak to be detected by HEXTE in such a short exposure. In this paper we will also present the ASCA observations that were made contemporaneously, as part of the cross-calibration program. These observations are not the same as presented by Saito et al. (1997a), but are described in more detail by Saito et al. (1997b).

For PSR B1509−58, we present proprietary observations made with the PCA in the same *GoodXenon* data configuration, and HEXTE observations using an event data configuration with 8 µs time resolution. These observations cover the period January through October 1996.

The observations were analyzed using the program faseBin, developed by one of us (AHR) and publicly distributed as part of the Ftools analysis package by the GSFC HEASARC. The program selects only good events, calculates the absolute pulse phase, based upon the radio pulsar timing ephemeris, and bins the photon events in a two-dimensional histogram of energy channel vs pulse phase.

The time from the FITS files is corrected to 8 µs accuracy and transformed from TT to TDB (Barycentric Dynamical Time), using the RXTE orbit ephemeris and the JPL DE-200 solar system ephemeris (see Standish 1982, Standish 1990). Both of these ephemerides are accurate to better than 1 µs. The uncertainty introduced by the TDB−TT term is approximately 2 µs. In summary, we feel confident that our time stamps are correct to 10 µs. The same code and ephemeris are used to transform the timing ephemeris to TDB.

The two-dimensional histograms are then collapsed over one or more energy ranges to create light curves as a function of absolute phase, or over one or more phase ranges to allow phase-resolved spectroscopy.

All X-ray pulse phases in this paper refer to the peak of the pulse. The timing ephemerides used are given in Table I.

In the near future, we intend to switch the faseBin program from the DE-200 to the DE-405 ephemeris. At this place, for future reference, we shall briefly deal with the issues involved in that change-over. Aside from higher accuracy, there are two fundamental changes and two possible sources of inconsistencies. The two fundamental changes are:

1. Although both ephemerides are based on the epoch J2000.0, DE-200 uses the older FK-5 reference system while DE-405 is tied to the International Celestial Reference System (ICRS), as adopted by the IAU at its 1997 General Assembly in Kyoto, Japan.

2. Due to more accurate masses of the solar system bodies, the position of the barycenter has shifted. The difference can amount to several milliseconds.
In tying X-ray observations to radio timing ephemerides, the two potential inconsistencies, as it turns out, do in many cases not cause a problem:

1. The radio timing ephemerides, till the present, have been derived using DE-200. Fortunately, this cancels out since the time of arrival of the pulse, or zero-phase, (column 5 in Table 1) is given in (i.e., converted back to) geocentric time, but only to the level of tens of micro-seconds. Hence, it cannot be ignored for milli-second pulsars. In the future, radio ephemerides will be based on DE-405, and an code will be provided indicating which planetary ephemeris has been used.

2. The spacecraft orbit ephemeris may be (and usually is) provided in J2000.0 geocentric coordinates referenced to FK-5. The error incurred by adding such vectors to J2000.0 ICRS vectors is proportional to the length of the geocentric FK-5 vector. Since the misalignment between the two reference systems is about 20 milli-arcseconds, the maximum error arising from this misalignment is approximately 2 ns times the distance of the spacecraft from the geocenter, expressed in earth radii. Hence, the error is definitely negligible, not only for spacecraft in low earth orbit like RXTE, but also for more elliptical orbits like AXAF.

### 4. PSR B1821−24

#### 4.1. Comparison with Jodrell Bank and ASCA Observations

The timing ephemeris was derived from observations made with the Jodrell Bank Mark IA radio telescope, at an observing frequency of 1408 MHz, assuming a dispersion measure of 119.86 pc cm$^{-3}$. The pulse profile, showing two pulse components is included in Fig. 1. In order to be consistent with the nomenclature in Backer and Sallmen (1997), we shall refer to the pulse component at phase 0.1 as number 2, the one at phase 0.8 as number 1. The time resolution of the observations was about 300 $\mu$s, or one-tenth of a period. The error in the determination of the dispersion measure leads to an uncertainty of about 150 $\mu$s, or about 0.05 in phase, at infinite frequency. The timing ephemeris is labeled in Table 1 as B1821−24J. Note that the zero point of the phase of this ephemeris is different from that of the Green Bank ephemeris.

The RXTE signal-to-noise ratio is such that we only present one light curve: PCA 2-16 keV (channel 5-49). There are two clear peaks, a narrow one at phase 0.8 and an asymmetric one at phase 0.3, consistent with the separation between the peaks seen in the ASCA result reported by Saito et al. (1997a) but slightly offset in phase. The narrow pulse component has a width less than 0.04 in phase, corresponding to 100 $\mu$s. Analysis of the two orbits separately shows that these two peaks are clearly present in both sets while all other features do not consistently appear in both; the latter must therefore be either spurious or time-variable and will not be considered here.
We present the RXTE light curve in Fig. 1, together with the ASCA GIS and radio light curves. The background level (internal and cosmic background, and unpulsed source) is included. The total pulsed flux is about 1% of the combined unpulsed flux and backgrounds. These data prove that it is possible to detect with RXTE a narrow pulsed signal with a flux of only 0.5% of the unpulsed flux in a single orbit observation.

When the original ASCA observations were reported on by Saito et al. (1997a), it was not at that time possible to compare the ASCA and radio phases in an absolute sense since the uncertainty in the ASCA clock was approximately 1 ms. This problem has been solved for the ASCA observations obtained in the context of the RXTE-ASCA clock cross-calibration project that are presented in this paper. The uncertainty in the ASCA clock has been reduced to 200 µs (see: Saito et al. 1997b) and all phases in Fig. 1 are calculated as absolute phases, applying all known clock corrections. The ASCA light curve exhibits the same features as the RXTE one, albeit that they are shifted by approximately 0.05 period in phase (≈ 150 µs). Errors of this magnitude have been observed in ASCA’s clock and attributed to drift due to temperature variations. Hence, we feel justified in assuming that RXTE’s absolute timing is the more correct one.

The phase information is summarized in Table 2. Note that this table uses the radio pulse component numbering from Backer and Sallmen (1997).

4.2. Comparison with Green Bank Observations

Recently, Backer and Sallmen (1997) published a new radio pulse profile of PSR B1821–24 based on observations made with the NRAO 42 m telescope at Green Bank, WV, at observing frequencies of 800 and 1395 MHz. Owing to the use of the Spectral Processor backend, the temporal resolution of the pulse profile is much higher than that of the Jodrell Bank one, revealing the existence of a third radio pulse component. Backer and Sallmen (1997) compared the result with ASCA observations, but no absolute phase comparison could be made. We have analyzed the RXTE observation using the timing ephemeris that was derived from the Green Bank observations (see Table 1, B1821–24G). The dispersion measure was, of course, determined for each observing session separately, based on the dual frequency data.

The resulting light curves, presented in Fig. 2, are quite convincing. There is good agreement between the narrow X-ray pulse component and radio pulse component 1, as correctly anticipated by Backer and Sallmen (1997), but the broad X-ray pulse component lags radio component 3 by about 0.08 period. The X-ray version of pulse component 1 seems to lag the radio component by

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7 Also: http://heasarc.gsfc.nasa.gov/docs/asca/newsletters/gis_time_assign5.html

8 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
60 µs which is not consistent with their being temporally coincident. The accuracy of the X-ray phase, 10 µs (see Section 3), is dominated by the uncertainty in the RXTE clock; the accuracy of the radio phase is approximately 10 µs (1σ), mainly due to uncertainty in the dispersion measure. We have summarized the phases of the pulse component peaks in Table 2. The quoted errors are approximate 1σ values. One should note that the difference between the pulse profiles derived from the Jodrell Bank and Green Bank observations, as shown in Figs. 1 and 2 is due in part to the difference in temporal resolution, but also in part to the difference in observing frequency. The spectral characteristics of the two components are very different at radio frequencies: at higher frequencies pulse component 2 is generally stronger than pulse component 1. The high resolution pulse profile at 1395 MHz presented by Backer and Sallmen (1997) provides an easier comparison.

It is interesting to note that, after the Crab pulsar, we have here, once again a pulsar where the main radio and X-ray pulse component peaks are coincident to better than 20 milli-periods.

This public RXTE observation only yielded 6559 s of exposure. Two of us (YS and NK) have obtained a proprietary observation of much longer duration. It seems prudent, therefore, to defer discussion of other characteristics, such as spectral properties, to the publication of those observations.

5. PSR B1509–58

The timing data for PSR B1509–58 were obtained using the Parkes telescope in a continuation of the observational program described by Kaspi et al. (1994); the observing frequency was 1400 MHz, the assumed dispersion measure 253.2 pc cm$^{-3}$. The radio pulse profile displays a single pulse component with a full width at half power of about 0.1 period; the phase is referenced to the peak of that pulse with an accuracy of about 1 ms. The timing ephemeris is provided in Table 1.

5.1. Timing Analysis

In X-rays, this pulsar has been monitored during the entire RXTE mission to date. The monitoring observations each lasted at least 2000 s and were done approximately once a month. Fig. 3 shows the light curves in the 2-16 keV PCA band for ten of these observations. The vertical line is drawn at phase 0.27. There are clearly variations in these light curves, but they are consistent with a constant (X-ray – radio) peak phase lag of 0.27 ± 0.01 period, as indicated by the distribution, in phase, of the peak bins of the ten light curves. We have also analyzed the cross-correlation functions between the ten light curves. The centroids are all distributed

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9The Parkes telescope is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility by CSIRO.
within 0.008 of the average. From this we conclude that the variation in phase is no more than 0.005 period, comparable to the uncertainty in the radio timing ephemeris. As a matter of fact, there appear to be systematic variations at this level that are correlated with the different timing ephemeris entries. Our phase lag result is consistent with the phase lag derived by Kawai et al. (1991) but is different from that determined by Ulmer et al. (1993). We will return to this issue in the discussion section, below. The shapes of the light curves agree with those obtained by both previous investigations.

Fig. 4 shows the accumulated light curves for the bands 2-4, 4-8, 8-16, 16-32, 32-64, 64-128 keV (the first four PCA, the last three HEXTE). These data are consistent with a phase lag of 0.27, independent of energy. Note that the changes in pulse profile with energy are probably not significant, as indicated by the spectral analysis, below.

5.2. Spectral Analysis

We performed phase-resolved spectral analysis, using the program XSPEC. For this purpose we accumulated PCA and HEXTE spectra in eight slices of 0.05 period, from phase 0.20 through phase 0.55. The average count rate spectrum in the phase range from 0.7 through 1.1 was used as the value for the unpulsed components of internal and cosmic background, as well as the source itself, and subtracted from spectra of the pulsed radiation. It transpired that the spectra could all be fit well with a simple power-law model with interstellar absorption (Morrison and McCammon 1983). On the basis of fits to spectra near the peak of the pulse, we adopted a value for $N_H$ of $6 \times 10^{22}$. Hence, only photon spectral index and total flux were allowed to vary. The somewhat surprising result is that all spectra are consistent with a single value for the photon index: $1.345 \pm 0.010$; i.e., the photon flux density (photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) is proportional to $E^{-1.345 \pm 0.01}$. The derived photon index values, with formal errors and reduced $\chi^2$, are listed in Table 3. Fig. 5 presents the spectral fit for phase 0.25. It is illustrative of the fits at other pulse phases.

The value for the photon index of 1.345 is consistent with the one obtained by Kawai et al. (1993). They found $1.30 \pm 0.05$. Matz et al. (1994) determined the index to be $1.68 \pm 0.09$ for the energy range 50 keV - 5 MeV, based on OSSE observations and speculated that there has to be a break in the spectrum between 20 and 80 keV. A broken power-law fit to our spectra does not improve the fit. Hence, we conclude that the break is most likely to occur above 50 keV. A more comprehensive spectral analysis has been presented by Marsden et al. (1997).

The surprise lies in the fact that there is no significant change of photon index with phase. Kawai et al. (1991) have speculated that there may be two components making up PSR B1509–58’s X-ray pulse shape. The light curves seem to support this notion. But if such is the case, then the two components are, at least to RXTE, spectrally indistinguishable.
5.3. Discussion

The significance of our results for the difference in phase lag between, on the one hand, this paper and Kawai et al. (1991), and, on the other, Ulmer et al. (1993) is considerable. Kawai et al. (1991) find a value of $0.25 \pm 0.02$ for the 2-11 keV band, which is consistent with the value we find of $0.27 \pm 0.01$ for the 2-16 keV band. This phase lag refers explicitly to the peak. Ulmer et al. (1993) find (fitting to the shape of the Kawai et al. 1991 light curve) a phase lag of $0.32 \pm 0.02$ for BATSE data covering the band 20-400 keV (the OSSE observation is less relevant in this context). We should also mention, at this point, the results from the balloon experiment “Welcome”, reported by Gunji et al. (1994). Covering the range 94-240 keV, these observations are consistent, both spectrally and temporally, with the Ginga data; the uncertainties preclude a stronger statement. The inconsistency with the Ulmer et al. (1993) result (8 ms) is especially troubling because the CGRO absolute time information is qualitatively much better than that of the other missions. It cannot be summarily dismissed as a CGRO clock or software error since such would have had very noticeable effects on, for instance, the Crab pulsar light curves from CGRO instruments.

We attempted to resolve the issue by reprocessing five years of BATSE observations of PSR B1509−58 from the public CGRO archive, using all data at energies higher than 32 keV. The result is shown in Fig. 6. Cross-correlation analysis of the pulse profiles reveals that the BATSE light curve is shifted by 0.03 period, or 5 ms. Although this difference is smaller than for Ulmer et al. (1993)’s result, it still exceeds the acceptable bounds, it is still too large to be unnoticed in the Crab data, and it raises the question why this BATSE time lag is different from what was found previously.

There are only two explanations possible that can reconcile the results of the three space-based investigations (Kawai et al. 1991, Ulmer et al. 1993, and the present paper): the phase lag varies with energy; or the phase lag varies in time.

Energy dependence seemed unlikely, judging from the full energy range of Ulmer et al. (1993)’s BATSE and OSSE observations, but remained possible. Our data show convincingly that there is no variation of phase lag over the range 2-100 keV. Even if the reader may not be persuaded by Fig. 7 that this statement applies above 50 keV, the hypothesis requires a considerable hardening of the spectrum at phases above 0.30; this is clearly ruled out by our spectral analysis. This is corroborated by the combination of Ginga and Welcome observations by Kawai et al. (1991) and Gunji et al. (1994) which make it seem very unlikely that a break in the spectrum would occur below 100 keV.

Time evolution of the phase lag was all but ruled out by Ulmer et al. (1993), on the basis of their BATSE and OSSE observations. This is corroborated by our data, at least on time scales of one year or less (Fig. 3). It is also worth mentioning that the radio ephemerides were created over short durations so that phase drift due to low level timing noise observed in the pulsar cannot be the cause of the discrepancy.
A change in the pulsar dispersion measure would result in an apparent change in phase offset between radio and X-ray energies. However, the dispersion measure change required to explain the discrepancy is over an order of magnitude larger than is expected based on similar results for most other pulsars (Backer et al. 1993 and references therein); it requires an increase of more than 0.5 pc cm$^{-3}$ per year. In our analysis we have used the value for the dispersion measure of 253.2 ± 1.9 pc cm$^{-3}$ given by Kaspi et al. (1994). This same value was used by all investigators quoted in the present paper. Recently (MJD 50780-50784), one of us (RNM) has made a new measurement of the dispersion measure and obtained a value of 255.3 ± 0.3 pc cm$^{-3}$ (2σ error). A preliminary analysis of nearly contemporaneous RXTE observations, using this new value, yields a phase offset of 0.29 ± 0.01. At first glance, this appears to resolve the inconsistency, and it very well may, but one has to be extremely careful: the two determinations of the dispersion measure are still marginally consistent with each other and there is no irrefutable evidence that the dispersion measure actually changed. If we just take the extremes as indicated by the quoted errors, the change in dispersion measure over seven years may have been anywhere between 0 and 4 pc cm$^{-3}$.

In conclusion, we note that a gradual change in dispersion measure from 253.2 pc cm$^{-3}$ in 1990 to 255.3 pc cm$^{-3}$ in 1997 would explain the changes in phase lag. But the plausibility of such a scenario needs to be confirmed by future monitoring of the dispersion measure.

Support for one of us (VMK) was provided by Hubble Fellowship grant number HF-1061.01-94A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. We are grateful to an anonymous referee for helpful comments.
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Fig. 1.— PSR B1821–24. Light curves based on (a) ASCA GIS (0.7-10 keV), (b) RXTE PCA (2-16 keV), (c) Jodrell Bank radio (1408 MHz) observations, using timing ephemeris B1821–24J. The ASCA light curve is labeled in total counts per bin (at 48 bins per period), the RXTE light curve in counts per second per bin (at 100 bins per period) with 1σ errors indicated. The instrumental broadening in the radio profile amounts to about 0.1 in pulse phase. Note that the zero point of the phase of this ephemeris used in this figure is different from the one used in Fig. 2.
Fig. 2.— PSR B1821−24. Light curves based on (a) RXTE PCA (2-16 keV), and (b) Green Bank radio (800 MHz) observations, using timing ephemeris B1821−24G. The RXTE light curve is labeled in counts per second per bin (at 100 bins per period) with 1σ errors indicated. The radio pulse components are identified using the same numbering as Backer and Sallmen (1997).
Fig. 3.— PSR B1509−58. Light curves for ten epochs (PCA 2-16 keV). The error bars represent 1σ errors. The vertical line indicates phase 0.27.
PSR B1509–58

Fig. 4.— PSR B1509–58. Accumulated light curves for seven energy bands. The vertical scale is arbitrary; the error bars represent 1σ errors.
Fig. 5.— PSR B1509−58. Spectral fit for pulse phase 0.25. The crosses (1σ error bars) in the upper panel represent the observations, the solid lines the model convolved with the response matrices. The left hand segment pertains to PCA data, the right hand segment to HEXTE data. The lower panel presents the ratio data/model.
PSR B1509−58

Fig. 6.— PSR B1509−58. Accumulated light curves based on (a) RXTE PCA (2-16 keV) and (b) BATSE (> 32 keV) observations. The error bars represent 1σ errors.
Table 1: Radio Timing Ephemerides

| Pulsar | RA (J2000.0) | Dec (J2000.0) | MJD Range | \( t_{0,\text{geo}} \) (MJD(UTC)) | \( \nu \) (s\(^{-1}\)) | \( \dot{\nu} \) (10\(^{-12}\)s\(^{-2}\)) | \( \ddot{\nu} \) (10\(^{-24}\)s\(^{-3}\)) | Rms\(^{a}\) |
|--------|--------------|--------------|-----------|----------------|----------------|----------------|----------------|--------|
| B1821–24\(^{b}\) | 18\(^{h}\)24\(^{m}\)32.008\(^{s}\) | -24\(^{\circ}\)52'11.12"ootnote{Based on Jodrell Bank observations} | 50059 - 50372 | 50215.0000000023 | 327.4056597973296 | -0.173520 | 0.0 | 22.2 |
| B1821–24\(^{c}\) | 18\(^{h}\)24\(^{m}\)32.008\(^{s}\) | -24\(^{\circ}\)52'10.70"ootnote{Based on Green Bank observations} | 47826 - 50660 | 49243.0000000025 | 327.4056743697863 | -0.173521 | 0.0581 | 6.8 |
| B1509–58 | 15\(^{h}\)13\(^{m}\)55.627\(^{s}\) | -59° 8’ 9.54"ootnote{Based on Green Bank observations} | 50114 - 50296 | 50205.0000000764 | 6.6267743270631 | -67.3824 | 1950 | 9.1 |
| B1509–58 | 15\(^{h}\)13\(^{m}\)55.627\(^{s}\) | -59° 8’ 9.54"ootnote{Based on Green Bank observations} | 50242 - 50462 | 50352.000000582 | 6.6259186740744 | -67.3579 | 1950 | 8.0 |

\(^{a}\)In milli-periods

Table 2: PSR B1821–24 Pulse Peak Phases

| Spectral band | Timing ephemeris | Pulse 1 | Pulse 2 | Pulse 3 |
|---------------|------------------|---------|---------|---------|
| X-ray (2-16 keV) | B1821–24J | 0.775 | | 0.31 |
| Radio (Jodrell Bank, 1408 MHz) | B1821–24J | 0.785 | 0.105 |
| X-ray (2-16 keV) | B1821–24G | 0.229 ± 0.003 | 0.77 ± 0.01 |
| Radio (Green Bank, 800 MHz) | B1821–24G | 0.209 ± 0.003 | 0.50 ± 0.01 | 0.69 ± 0.01 |

Table 3: PSR B1509–58 Fitted Photon Index as a Function of Phase

| Phase | Net Count Rate | Photon Index | Error | Reduced \( \chi^2 \) |
|-------|---------------|--------------|-------|------------------|
| 0.20  | 29.2          | 1.389        | 0.027 | 0.909            |
| 0.25  | 45.2          | 1.356        | 0.018 | 1.097            |
| 0.30  | 43.4          | 1.341        | 0.018 | 1.050            |
| 0.35  | 37.6          | 1.343        | 0.021 | 1.021            |
| 0.40  | 34.5          | 1.342        | 0.022 | 1.081            |
| 0.45  | 29.0          | 1.341        | 0.026 | 0.861            |
| 0.50  | 20.3          | 1.419        | 0.037 | 1.261            |
| 0.55  | 12.8          | 1.397        | 0.056 | 0.838            |