A COHERENT TIMING SOLUTION FOR THE NEARBY ISOLATED NEUTRON STAR RX J0720.4–3125

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ABSTRACT

We present the results of a dedicated effort to measure the spin-down rate of the nearby isolated neutron star RX J0720.4–3125. Comparing arrival times of the 8.39-sec pulsations for data from Chandra we derive an unambiguous timing solution for RX J0720.4–3125 that is accurate to < 0.1 cycles over > 5 years. Adding data from XMM and ROSAT, the final solution yields \( \hat{P} = (6.98 \pm 0.02) \times 10^{-14} \text{ s}^{-1} \); for dipole spin-down, this implies a characteristic age of 2 Myr and a magnetic field strength of \( 2.4 \times 10^{13} \text{ G} \). The phase residuals are somewhat larger than those for purely regular spin-down, but do not show conclusive evidence for higher-order terms or a glitch. From our timing solution as well as recent X-ray spectroscopy, we concur with recent suggestions that RX J0720.4–3125 is most likely an off-beam radio pulsar with a moderately high magnetic field.

Subject headings: pulsars: individual (RX J0720.4–3125) — stars: neutron — X-rays: stars

1. INTRODUCTION

One of the interesting results from ROSAT All-Sky Survey (Voges et al. 1999) was the discovery of seven objects that appear to be nearby, thermally-emitting neutron stars that have little if any magnetospheric emission (see Haberl 2004 for a review). These objects, known most commonly as “isolated neutron stars,” are distinguished by their long periods (\( > 3 \text{ s} \), when measured), largely thermal spectra with cool temperatures (\( kT \lesssim 100 \text{ eV} \)), faint optical counterparts (when detected), and lack of radio emission.

It is not yet clear what sets the isolated neutron stars apart from the nearby, relatively young rotation-powered pulsars that also have cool thermal emission like PSR B0656+14 and PSR B1055–52 — which tend to have short (\( < 1 \text{ s} \)) spin periods, \( \sim 10^{12} \text{ G} \) magnetic fields, non-thermal (i.e. power-law) components in their X-ray spectra, and radio pulsations (e.g., Pavlov & Zavlin 2003; Kaplan 2004). The isolated neutron stars are known to have longer periods, but their spin-down rates (and hence magnetic fields) are unknown, largely because it has not yet been possible to determine a reliable, coherent timing solution (Kaplan et al. 2002 hereafter Paper I; Zane et al. 2002).

In this Letter we report a new analysis of the variations of the 8.39-s period of the second brightest source of the group, RX J0720.4–3125 (Haberl et al. 1997). We describe our analysis of Chandra data obtained specifically for timing purposes, as well as archival ROSAT, Chandra, and XMM data, in §2. In §3 we show that with the new data, we can avoid the pitfalls of the previous phase-coherent timing analyses and obtain a reliable timing solution. We discuss possible timing noise in §4 and the implications of our result in §5.

2. OBSERVATIONS

Our primary data were eight observations with the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) aboard the Chandra X-ray Observatory (CXO; Weisskopf et al. 2000). These were designed for timing accuracy, consisting of two sets of four exposures geometrically spaced over a period of about two weeks and separated by about half a year. We combined these data with other Chandra observations, as well as from observations with XMM-Newton (Jansen et al. 2001) and ROSAT (Trümper 1993). A log of all observations is given in Table I.

For the Chandra data, we processed the level-1 event lists to the level-2 stage following standard procedures and the latest calibration set (CALDB version 3.0.0). For the ACIS continuous-clocking data, this includes correcting the recorded event times for readout, dither, and spacecraft motion — corrections that used to require additional steps (Zavlin et al. 2001). We extracted events within 1″ of the source, and then applied a clock correction of 281.7 μs to the arrival times (Davis, Holmes, & Myers 2003); the arrival times should now be accurate to \( \lesssim 6 \mu \text{s} \). For the HRC-S/LETG data, we extracted zeroth-order events from a circle with radius 10 pixels (1″), and first-order events using the standard LETG spectral extraction windows, but limited to \( 10 \lesssim \lambda \lesssim 65 \text{Å} \). Finally, we used the axbary program to barycenter all of the events (using the optical position: \( \alpha_{2000} = 07^{h}20^{m}24^{s}.96, \delta_{2000} = -31^{\circ}25'50''/2; \) Kaplan et al. 2003).

For the XMM data, we used the standard procedures emchain and epchain (XMMAS version 6.1.0) to reprocess the observations. One additional step was necessary for the PN data set 622-U2, for which we found a small number of duplicate events (frames 963685–963719); we removed these before processing. Next, we extracted all single-pixel events within 37.5″ of the source position, and used barycen to convert the arrival times to the solar-system barycenter.

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4 Some portions of the 2000 and 2002 XMM/PN observations were affected by a known processing problem
TABLE 1
LOG OF OBSERVATIONS AND TIMES OF ARRIVAL

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<tr>
<th>Instrument</th>
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</table>

aPSPC: Position Sensitive Proportional Counter (Briel & Pfeffermann 1995) aboard ROSAT. HRI: High-Resolution Imager (Zombeck et al. 1995) aboard ROSAT. HRC: High-Resolution Camera for spectroscopy aboard Chandra (HRC-S; Kraft et al. 1997), used with the Low-Energy Transmission Grating. ACIS: Chandra’s Advanced CCD Imaging Spectrometer (Garmire et al. 2003), used in continuous clocking mode. EPIC-pn: XMM’s European Photon Imaging Camera with PN detectors (Strüder et al. 2001), used in full-frame (ff) or small window (sw) mode, with thin, medium, or thick filter. EPIC-MOS1/2: European Photon Imaging Cameras with MOS detectors aboard XMM (Turner et al. 2001), used in small-window mode with thin or no (open) filter.
bObservation identifier (CXO, ROSAT) or revolution number and exposure identifier (XMM).
cThe TOA is defined as the time of maximum light closest to the middle of each observation, and is given with 1-σ uncertainties.

The reduction of the ROSAT data followed that in Paper I, except that we properly corrected the event times to the Barycentric Dynamical Time (TDB) system instead of the Coordinated Universal Time (UTC) system returned by the FTOOLS barycentering tasks (see Cropper et al. 2004). We used the corrections supplied in Cox (2000, p. 14).

that rejected significant portions of the observations; see http://xmm.vilspa.esa.es/sas/documentation/watchout/lost_events.shtml.
This should not introduce any systematic error, though it means that our TOAs for these observations are not as precise as possible with all events. However, since the present TOA uncertainties are smaller than the timing noise ($\sigma$), we decided not to try to remedy this problem.

3. TIMING ANALYSIS

Our goal was to use times-of-arrival (TOAs) to infer a phase-coherent timing solution involving the spin period and its derivative, where each cycle of the source was counted. To measure TOAs we needed an initial reference period, something which we determined using a $Z^2_1$ test (Rayleigh statistic; Buccheri et al. 1983) on the combined 2004 January ACIS and 2004 February HRC data. We find $P = 8.391159(10)$ s (here and below, numbers in parentheses indicate twice the formal 1-σ uncertainties in the last digit unless otherwise indicated), which is consistent with our earlier value (Paper I) but much more accurate because we could coherently connect observations over a much longer (52 day) time span.

Using this period, we constructed binned light curves
observations gave that the resulting solutions were very poor (e.g., altering more cycles) at the least unambiguous points, but found changing the cycle counts (adding or subtracting one or more) to test the uniqueness of our ephemeris, we tried Chandra reference time added in quadrature). The vertical dashed line indicates the reference period to determine cycle counts for the five data in Table 1.

We then determined a timing solution for only the Chandra data using an iterative procedure. We first used the reference period to determine cycle counts for the five above-mentioned observations, as well as the next observation closest in time. We fit these cycle counts to

$$\phi(t) = \phi_0 + \nu(t - t_0) + \frac{1}{2} \nu^2(t - t_0)^2 + \frac{1}{6} \nu^3(t - t_0)^3 \ldots,$$

where $\phi_0$ is the cycle count plus phase at reference time $t_0$, $\nu$ is the spin-frequency, $\dot{\nu}$ is its derivative, $\ddot{\nu}$ is the second derivative. We then iterated, using the improved solution to determine the cycle count for the next observation, etc. We started with $\dot{\nu} = \ddot{\nu} = 0$, but left $\nu$ free once that significantly improved the fit; $\ddot{\nu}$ was not required (cf., § 4 below).

The final ephemeris listed in Table 2 has small, ≤ 0.1 cycle, residuals, and fits the Chandra data well: $\chi^2_\nu = \chi^2 / N_{\text{dof}} = 1.06$ (with $N_{\text{dof}} = 13$ degrees of freedom). To test the uniqueness of our ephemeris, we tried changing the cycle counts (adding or subtracting one or more cycles) at the least unambiguous points, but found that the resulting solutions were very poor (e.g., altering the cycles between the 2001 ACIS and 2000 HRC observations gave $\chi^2_\nu = 89.26$).

To improve and extend the ephemeris, we added the XMM and ROSAT data into the solution (see Table 2). As for the Chandra data alone, the cycle counts are unambiguous and, as can be seen in Fig. 1, the residuals remain below 0.1 cycles, lending additional credence to our results. For verification, we also examined the fit using just the Chandra and XMM data, which avoids the large gaps between the ROSAT observations. We found the same cycle counts, but a statistically significant difference in the inferred parameters ($\nu = 0.11917366887(12) \text{ Hz}$ and $\dot{\nu} = -9.69(4) \times 10^{-16} \text{ Hz s}^{-1}$, while the fit to all data gave $\nu = 0.1191736700(2)$ and $\dot{\nu} = -9.915(14) \times 10^{-16} \text{ Hz s}^{-1}$).

While we are confident in our fit in general, the above discrepancy is puzzling. Furthermore, the $\chi^2$ values for the fits including the XMM data are poor, with $\chi^2 = 6.16$ for Chandra+XMM ($N_{\text{dof}} = 28$; rms = 0.34 s) and $\chi^2 = 10.25$ for all of the data ($N_{\text{dof}} = 31$; rms = 0.36 s), while the solution for Chandra+ROSAT, although somewhat ambiguous, is tolerable ($\chi^2 = 1.40$) and similar to the Chandra-only solution. The $\chi^2$ values for the full fits are dominated by the contribution of the XMM data, which have very small formal uncertainties (but are not always entirely consistent from one instrument to another for the same observation; see Tab. 1). The XMM data also cause the values of $\dot{\nu}$ to differ by 3% and the Chandra+XMM ephemeris to be a poor match to the ROSAT points. We discuss these deviations in more detail below; here, we note that for the estimates of the values and uncertainties in Table 2 we ensured $\chi^2 \approx 1$ by adding in quadrature an additional uncertainty of 0.27 s to all TOAs. We stress, however, that our overall solution is robust, and the inferred spin-down rate should be reliable at the <3% level.

### 4. Deviations from Regular Spin Down?

There could be several reasons for the relatively poor fit of the timing solutions to our full set of arrival times. First, RX J0720.4–3125 may show some rotational instabilities or “timing noise,” as seen in radio pulsars. We can estimate the magnitude of the long-term timing noise...
by fitting the phase residuals with a third-order ($\dot{\nu} \neq 0$) solution like that shown in Fig. 1. This does in fact improve the fit — giving $\chi^2_r = 6.02$ for $N_{\text{data}} = 30$ with an rms of 0.32 s — though it is still formally unacceptable. We find $\ddot{\nu} \approx 2.4(4) \times 10^{-25}$ Hz s$^{-2}$ (this also changes $\dot{\nu}$ by 3% from the value in Tab. 2), giving a timing noise measurement of $\Delta s = \log_{10}|\ddot{\nu}|(10^8/6\nu) = -0.5$. This value is on the high side of, but not outside the range expected from relations between $\dot{P}$ and $\Delta s$ found for radio pulsars (Arzoumanian et al. 1994) and magnetars (Woods et al. 2000; Gavriil & Kaspi 2002). We do not believe it is likely that the third-order solution represents a real long-term change in $\dot{\nu}$, since the value of $\ddot{\nu}$ changes significantly if one uses just the Chandra, Chandra+XMM, or all of the data$^5$ [8(6), 18(4), or 2.4(4) $\times 10^{-25}$ Hz s$^{-2}$, with $\chi^2_r = 0.64, 2.81, or 6.02$ respectively].

A second possibility is a sudden change in rotation — a glitch, as proposed (and largely rejected) by de Vries et al. (2004) to account for variations in spectral shape (differences of 10% in the inferred temperature) and pulse shape (changes of 50–100% in pulsed fraction) observed between 2000 and 2003. The systematic increase in the residuals after MJD 53000 in Figure 1 might indeed indicate a glitch. We tried fitting a simple glitch model, in which we assumed that only the frequency changed, that the recovery time was longer than the span of our observations, and that the glitch occurred on 2003 July 1 (MJD 52821), in between the two XMM observations that showed the largest spectral change (de Vries et al. 2004). We find a reasonable fit for a glitch with $\Delta f = 1.3 \times 10^{-9}$ Hz and a recovery time $\tau > 3$ yr, giving $\chi^2_r = 7.7$ (see Fig. 1). This would be a small glitch, with $\Delta f / f = 1.1 \times 10^{-8}$ compared to values of $10^{-6}$ to $10^{-5}$ for radio pulsars (with smaller values more typical for larger magnetic fields; Lyne, Shemar, & Smith 2004). It also implies that energetically, the putative glitch would be insignificant: the change in kinetic energy of $\sim 10^{40}$ ergs (van Riper et al. 1991) would only be noticeable if dissipated in $< 1$ day given the bolometric luminosity of RX J0720.4–3125 of $\sim 2 \times 10^{42}$ergs s$^{-1}$ (where $d = 300$ kpc is the distance to RX J0720.4–3125; Kaplan et al. 2003). In principle, however, it could still have altered the light curve and spectrum of RX J0720.4–3125 through realignment of the magnetic field relative to the spin axis.

Finally, a more mundane explanation for the relatively poor fit is that the data are from different instruments with different energy responses (even among a single instrument aboard XMM, the changing filters alter the response). The pulse profile of RX J0720.4–3125 is known to depend on energy (Cropper et al. 2004; Paper I; Haberl et al. 2004) and to change over time (de Vries et al. 2004). While the changes to the shape are small, some systematic offsets are expected between the pulse profiles as measured by different instruments or at different times. We hope to investigate this in more detail in the near future.

At present, we cannot distinguish between the various possibilities for the relatively poor fits. The predicted future behavior is different, however, and thus further observations of RX J0720.4–3125 (some of which are in progress) should be able to distinguish between these models.

5. DISCUSSION & CONCLUSIONS

From our timing solution, we infer a spin-down rate $\dot{P} = 6.98(2) \times 10^{-14}$ s$^{-1}$. This is consistent with the limits derived in Paper I and by Zane et al. (2002), but inconsistent with the tentative solution of Cropper et al. (2004), who found $\dot{P} = (1.4 \pm 0.6) \times 10^{-13}$ s$^{-1}$ at 99% confidence (but who noted that elements of their solution were inconsistent with each other and that their analysis was subject to confusing aliases). In Table 2 we list derived parameters — rotational energy loss rate, magnetic field, and characteristic age (the latter two under the assumption of magnetic dipole spin-down).

The values of $P$ and $\dot{P}$ place RX J0720.4–3125 well above above most of the radio-pulsar “death-lines” proposed so far (e.g., Young, Manchester, & Johnston 1999) and in a region populated by radio pulsars in $P$–$P'$ diagrams like that in Paper I (its parameters are approximately between those of PSR J1830–1135, with $P = 6.2$ s, $\dot{P} = 5 \times 10^{-14}$ s$^{-1}$, and PSR J1847–0130, with $P = 6.7$ s, $\dot{P} = 1.3 \times 10^{-12}$ s$^{-1}$). Hence, RX J0720.4–3125 may well be a radio pulsar itself, but one whose radio beam(s) do not intersect our line of sight. Its inferred magnetic field, $B = 2.4 \times 10^{13}$ G, is not exceptional; the Parkes Multi-beam Survey (Manchester et al. 2003) in particular has discovered a fair number of radio pulsars with $B > 10^{13}$ G (e.g., Camilo et al. 2004; Morris et al. 2002; McLaughlin et al. 2003), and it is now clear the distribution of magnetic fields is flatter than previously assumed (Vranesic et al. 2004).

With $E = 4.7 \times 10^{30}$ ergs s$^{-1}$, RX J0720.4–3125 is not expected to have much non-thermal X-ray emission: from the relation of Becker & Trümper (1997), one estimates $L_X \approx 10^{-3} E \approx 5 \times 10^{27}$ ergs s$^{-1}$, much smaller than the thermal emission, $L_X \approx 10^{32}$ ergs s$^{-1}$. This is consistent with limits from Chandra and XMM (Pavels et al. 2004; Pavlov, Zavlin, & Sanwal 2003; Kaplan et al. 2003).

What is somewhat puzzling is the inferred age of 2 Myr. Tracing RX J0720.4–3125 back to OB associations where it might have been born put it close to the Trumpler 10 association $\sim 0.7$ Myr ago (Motch, Zavlin, & Haberl 2003; Kaplan 2004). Similarly, based on its estimated temperature and luminosity, most standard cooling models (modified URCA for 1.4 $M_\odot$ neutron stars) put RX J0720.4–3125 at $\lesssim 1$ Myr (HevI & Hernquist 1998; Paper I; Cropper et al. 2004).

It is of course possible that RX J0720.4–3125 was born with a long period and/or had significantly non-dipole braking, such that the spin-down age is not a good estimate of its true age. However, no case with as long a birth period as would be required for RX J0720.4–3125 is known among radio pulsars (cf. Kramer et al. 2003; Gavriil et al. 2004).

Another possible explanation is that RX J0720.4–3125 was ejected from a binary system with a massive companion $\sim 0.7$ Myr ago, either when the companion underwent a supernova or during a binary exchange inter-
action. In this case, a relatively long period is expected: if the neutron star accreted matter from its companion, its spin period would have tended toward the equilibrium period, $P_{eq} \approx 5 \times (B/10^{13} \, G)^{6/7} (M/M_{\text{Edd}})^{-3/7}$ (where $\dot{M}$ is the accretion rate and $M_{\text{Edd}}$ is the Eddington rate). A relatively short cooling age would also be consistent with this model: the accretion and accompanying steady hydrogen burning could reheat the neutron star (or keep it hot). Of course, it remains to be seen that a suitable evolutionary scenario can be found. In any case, the prediction for the model with two supernovae is that there may well be another $\leq 1$ Myr old neutron star whose proper motion traces back to the same origin as RX J0720.4−3125 (cf. Vlemmings et al. 2004).

Finally, we can compare the magnetic field strength of $2.4 \times 10^{13} \, G$ with what is inferred from the broad absorption feature in the spectrum (observed to be at $0.3 \, \text{keV}$, which corresponds to $0.39 \, \text{keV}$ at the surface for a gravitational redshift of 0.3; [Haberl et al. 2004 Vink et al. 2004]). If due to a proton cyclotron line, one infers $B \approx 6 \times 10^{13} \, G$ [Haberl et al. 2004], which is substantially larger than inferred from the spin-down. This may simply reflect the inadequacy of the dipole spin-down model, or the presence of higher order multipoles. On the other hand, based on a comparison with other sources, van Kerkwijk et al. (2004) suggested that the absorption feature was due to the transition from the ground state to the second excited tightly bound state of neutral hydrogen, which would require $B \approx 2 \times 10^{13} \, G$ and matches the spin-down value nicely. If that is the case, higher signal-to-noise spectra should reveal the transition to the first excited state at $\sim 0.15 \, \text{keV}$.

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