A COHERENT TIMING SOLUTION FOR THE NEARBY, THERMALLY EMITTING ISOLATED NEUTRON STAR RX J0420.0–5022

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ABSTRACT

We present a phase-coherent timing solution for RX J0420.0–5022, the coolest ($kT \approx 45$ eV) and fastest-spinning ($P = 3.45$ s) of the seven so-called isolated neutron stars (INSs). Using 14 observations with the XMM-Newton spacecraft in 2010 and 2011, we were able to measure a spin-down rate $\dot{\nu} = (-2.3 \pm 0.2) \times 10^{-15}$ Hz s$^{-1}$ ($P = (2.8 \pm 0.3) \times 10^{-14}$ s s$^{-1}$), from which we infer a dipolar magnetic field of $1.0 \times 10^{13}$ G. With reasonable confidence we were able to extend the timing solution back to archival XMM-Newton from 2002 and 2003, giving the same solution but with considerably more precision. This gives RX J0420.0–5022 the lowest dipole magnetic field of the INSs. Our spectroscopy does not confirm the broad absorption feature at 0.3 keV hinted at in earlier observations, although difficulties in background subtraction near that energy make conclusions difficult. With this, all six of the INSs that have confirmed periodicities now have constrained spin-downs from coherent solutions. The evidence that the INSs are qualitatively different from rotation-powered pulsars now appears robust, with the six of the INSs that have confirmed periodicities now have constrained spin-downs from coherent solutions.

Key words: stars: individual (RX J0420.0-5022) – stars: neutron – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

The so-called isolated neutron stars (INSs; see Haberl 2007 and Kaplan 2008 for reviews) are a group of seven nearby ($\lesssim 1$ kpc) neutron stars with low ($\sim 10^{32}$ erg s$^{-1}$) X-ray luminosities and long (3–10 s) spin periods (Kaplan & van Kerkwijk 2009b). They are unique in that the X-ray emission likely comes from a large fraction of the neutron stars’ surfaces and is not influenced by accretion (as in the case of X-ray binaries) or non-thermal magnetospheric emission (as in the case of rotation-powered pulsars); the INSs are also radio quiet (e.g., Kondratiev et al. 2009). The INSs then have the potential to help us understand neutron-star radii and cooling via measurements of their emission areas and luminosities, but this is made difficult by our inability to realistically model the X-ray, ultraviolet, and optical emission from these objects (e.g., Ho et al. 2007; Kaplan et al. 2011).

Recently it was proposed (Kaplan & van Kerkwijk 2009b; Pons et al. 2009; Popov et al. 2010) that the current temperatures and magnetic fields of the INSs reflect non-thermal, coupled evolution, where the magnetic field has decayed in strength, heating the neutron-star surface. Testing this hypothesis is an important step to using the INSs to constrain the overall cooling history of neutron stars, and through it to probe their inner structure and composition (Yakovlev & Pethick 2004). To constrain evolutionary models, measurements of the current magnetic fields and temperatures of the INSs are required. Similarly, to understand the broad absorption features seen at energies of 0.2–0.75 keV in the spectra of almost all INSs (Haberl 2007; van Kerkwijk & Kaplan 2007) also requires knowledge of the magnetic fields, as at these field strengths the assumed transition energies are field-dependent. Therefore, we have undertaken systematic measurements of the dipole magnetic fields for the INSs through phase-coherent X-ray timing using the Chandra and XMM-Newton spacecraft (Kaplan & van Kerkwijk 2005a, 2005b; van Kerkwijk & Kaplan 2008; Kaplan & van Kerkwijk 2009a, 2009b, hereafter KvK05a; KvK05b; vKK08; KvKvK09; KvKvK09b).

Here we measure the spin-down of the INS RX J0420.0–5022 (hereafter RX J0420), the last INS with a confirmed period measurement but without a timing solution. RX J0420 was identified as a possible neutron star by Haberl et al. (1999), although it had originally been associated with a nearby galaxy. Follow-up ROSAT observations showed a very soft thermal spectrum and yielded an improved position, both of which led to its classification as a neutron star. While initially a 22.7 s period was suggested, observations with XMM found a period of 3.45 s instead, the shortest among all INSs (Haberl et al. 2004, hereafter H+v04); the same observations also showed that RX J0420 was the coolest INS, with $kT \approx 45$ eV.

2. OBSERVATIONS AND ANALYSIS

We observed RX J0420 14 times with XMM (Jansen et al. 2001) in 2010 and 2011, and focus here on the data taken with the European Photon Imaging Camera (EPIC) with pn and MOS detectors, all used in the small-window mode with thin filters (Table 1). We reprocessed our observations with SAS version 11.0.0 and calibration files current as of 2011 May 25. We also reprocessed the pn data from H+v04, which are taken with the same filter, but with the full window mode instead (we did not use their full-frame MOS data, since these do not resolve the pulsations). We used emchain and epchain and selected source events from a circular region of 37.5 radius. For the pn, we selected energies between 130 and 800 eV, where we set our lower energy cutoff slightly below the default of 150 eV to increase the net number of counts from our very soft target (by about 25%; for even lower thresholds, the instrumental background increases too rapidly), and the upper cutoff at the energy at which the source becomes undetectable.
hardness ratio, and median energy were all consistent with no noise. We also checked to see if the true period was in fact the same as that found by Ptak et al. (2007); we will return to this alias shortly. We were able to identify the same solution using a single coherent periodogram for the composite, background-corrected pn data, but differences in background subtraction and energy selection could account for the difference (our best fit to the 2002 and 2003 data has a semi-amplitude of about 13% from KVV09b). This is a little higher than the semi-amplitude of about 10% from H+04, but differences in background subtraction and energy selection could account for the difference (our best fit to the 2002 and 2003 data has a semi-amplitude of 13.2% ± 1.1%). The \( \chi^2 \) for the fit to the composite profile was good, 14.4 for 13 dof.

Using our TOAs, we were able to identify a reasonably unambiguous coherent timing solution. This was possible as we restricted solutions to have \( |v| < 9 \times 10^{-13} \text{Hz s}^{-1} \) or \( B_{\text{ dip}} < 2 \times 10^{14} \text{G} \) (based on the incoherent limits set by Haberl 2007). Among those, the solution presented in Table 2 was the best, yielding \( \chi^2 = 19.9 \) for 11 degrees of freedom, with alternatives at \( \chi^2 = 25.1 \) (B dip = 1.8 \times 10^{14} G), \( \chi^2 = 37.3 \) (B dip = 7 \times 10^{13} G), and \( \chi^2 = 38.5 \) (v > 0). Of these, all but the first can be excluded on statistical grounds. The first comes from an uncertainty of ±1 cycle in the cycle count between the densely sampled Rev. 1981–1983 group and the next closest observation, Rev. 1975, and is close to the limit from Haberl (2007); we will return to this alias shortly. We were able to identify the same solution using a single coherent periodogram (as in KVV08). Spin-down is well detected at \( \approx 10 \sigma \). The reduced \( \chi^2 \) is somewhat high, but even adjusting our uncertainties to allow for a reduced \( \chi^2 \) of 1 will still give an 8\sigma detection of spin-down. The implied magnetic field is well within the range of other detections for the INSs (KVV09b).

We can confirm and improve our solution by extrapolating it back to the older data from 2002 to 2003. The time difference variation between the first and second halves of the pulse (with 16 bins the light curve variation between the first and second halves has \( \chi^2 = 10.6/8 \), while the hardness ratio variation has \( \chi^2 = 4.1/8 \). Using the above frequency, we determined the times of arrival (TOAs; see Table 1) for the combined EPIC data from each observation by fitting the binned light curves (following KVV05b) to a single sinusoid, appropriate given the results of the periodograms (Figure 1): the best-fit sinusoid to the composite, background-corrected pn data had a semi-amplitude of 15% ± 2%, where the uncertainty includes an estimate for the variation in the background correction over different background regions. This is a little higher than the semi-amplitude of about 10% from H+04, but differences in background subtraction and energy selection could account for the difference (our best fit to the 2002 and 2003 data has a semi-amplitude of 13.2% ± 1.1%). The \( \chi^2 \) for the fit to the composite profile was good, 14.4 for 13 dof.

2.1. Timing Analysis

Our timing analysis largely follows the procedure described in KVV05a. As a starting place, we first determined the frequency that maximized the power in a Z^2/2 periodogram for the EPIC-pn data from the longest observation in Rev. 1981. We then expanded the periodogram to include data from all observations in Revs. 1981 and 1983, finding a best-fit frequency of \( v = 0.2896033 \pm 0.0000003 \text{Hz} \), consistent with that found by H+04 for the earlier data. In contrast to some of the other INSs, there is no evidence for higher harmonics in the periodogram: the Z^2/2 power is 33.8, while Z^2/3 = 34.7 and Z^3/2 = 35.2, both of which are consistent with the additional power of 1 expected for noise. We also checked to see if the true period was in fact 6.9 s (closer to that of the other INSs), but the pulse shape, hardness ratio, and median energy were all consistent with no

### Table 1

| Rev. | Date       | Exp. (ks) | Counts (s) | f_\text{bg} (%) | TOA (MJD TDB) |
|------|------------|-----------|------------|-----------------|---------------|
| 560  | 2002 Dec 30| 20,047    | 4021       | 10.0            | 52638.2855519(12) |
| 561  | 2002 Dec 31| 20,048    | 4593       | 11.7            | 52640.0466236(12) |
| 570  | 2003 Jan 19| 20,547    | 4647       | 11.6            | 52658.8319656(8) |
| 664  | 2003 Jul 25| 20,036    | 4384       | 11.8            | 52506.0226435(10) |
| 1887 | 2010 Mar 30| 7472      | 2062       | 41.2            | 55285.5413317(17) |
| 1890 | 2010 Apr 4  | 9072      | 2679       | 45.8            | 55290.8432112(23) |
| 1892 | 2010 Apr 9  | 7772      | 2049       | 35.4            | 55295.4037368(11) |
| 1913 | 2010 May 21 | 5471      | 1462       | 32.1            | 55337.2671247(20) |
| 1948 | 2010 Jul 29 | 6472      | 1626       | 37.2            | 55406.6382597(30) |
| 1975 | 2010 Sep 21 | 9872      | 2372       | 38.2            | 55460.4233059(20) |
| 1981 | 2010 Oct 2  | 11,672    | 2980       | 34.8            | 55465.1049984(22) |
| 1981 | 2010 Oct 3  | 12,972    | 3064       | 38.6            | 55472.8839787(11) |
| 1981 | 2010 Oct 4  | 16,871    | 4465       | 40.2            | 55473.3194015(13) |
| 1983 | 2010 Oct 6  | 10,471    | 2586       | 36.9            | 55476.0218532(19) |
| 2008 | 2010 Nov 26 | 5471      | 1393       | 32.0            | 55526.4316848(19) |
| 2032 | 2011 Jan 13 | 15471     | 4223       | 44.5            | 55575.0260821(17) |
| 2071 | 2011 Mar 31 | 7018      | 1577       | 38.2            | 55651.9068660(24) |
| 2076 | 2011 Apr 11 | 5471      | 1248       | 32.2            | 55662.3338203(19) |

Notes. All observations used the small-window mode and thin filter for both EPIC-pn and EPIC-MOS1/2, except for Revs. 560, 561, 570, 664, in which the full window mode was used (which meant that only the EPIC-pn data were suitable for timing).

a The exposure time, number of counts, and estimated fraction of events due to background \( f_\text{bg} \) given here are for EPIC-pn only.

b The TOA is defined as the time of maximum light of the fundamental closest to the middle of each observation computed from the combined EPIC-pn and EPIC-MOS1/2 data sets, and is given with 1σ uncertainties.
is roughly 2600 days and our \( \bar{\nu} \) uncertainty gives a formal cycle-count uncertainty of \( \pm 5 \) cycles, but by trying multiple solutions, we find that only a single cycle count difference leads to a solution that fits all four earlier TOAs. Trying this generally, iteratively exploring all cycle-count ambiguities between all data sets, we find that only a single cycle count difference leads to a solution that fits all four earlier TOAs.

Notes. Quantities in parentheses are the formal 1\( \sigma \) uncertainties; \( \chi^2 \) is the characteristic age, assuming an initial spin period \( P_0 \equiv P \) and a constant magnetic field; \( B_{\text{dip}} = 3.2 \times 10^{19} \frac{\sqrt{P}}{T} \ G \) is the magnetic field inferred assuming spin-down by dipole radiation; \( \bar{E} = 3.9 \times 10^{49} \nu \bar{\nu} \ \text{erg s}^{-1} \) is the spin-down luminosity.

### 2.2. Spectroscopic Analysis

We examined all EPIC-pn spectra of RX J0420. (A full spectral analysis, including the EPIC-MOS and reflection grating spectrometer data and a phase-resolved analysis, is in progress.) We used the same source and background extraction regions as for the timing analysis, created appropriate response files, and binned the spectral files such that the number of source plus background counts was at least 25 and the bin width was at least 30 eV (so that there are roughly two bins per EPIC-pn resolution element).

We first compared the raw EPIC-pn spectra of all of the observations against each other. This did not include any response files or calibration corrections, but even so the binned pn spectra were generally consistent with each other, implying no spectral change (Figure 2). There are small deviations at low energies (0.2–0.4 keV) and we will return to these below, but the 2010 and 2011 data did not show any appreciable variability.

We fit the pn data using sherpa (Refsdal et al. 2009). To aid in fitting we merged the event and response files into two groups: one for 2002–2003 (full-frame data, also fit by H+04) and one for 2010–2011 (small-window data). While not perfect, we found that an absorbed blackbody provided a reasonable fit, with \( N_H < 1 \times 10^{18} \ \text{cm}^{-2} \), \( kT_{\infty} = 47.6 \pm 0.3 \ \text{eV} \), and \( R_{\infty} = 12.8 \pm 0.3 \ \text{km kpc}^{-1} \) (formal 1\( \sigma \) uncertainties; \( \chi^2 = 73.0 \) for 31 dof), reasonably consistent with H+04. Unlike H+04, we do not find evidence for a spectral feature, perhaps because of changes in the response files and calibration since earlier fits. However, there are indications that our fit is not completely reliable. First, the best-fit value of the absorption is 0 (although it is covariant with the blackbody temperature).

Second, there are some residuals near 0.33 keV, where H+04, we do not find evidence for a spectral feature, perhaps because of changes in the response files and calibration since earlier fits. However, there are indications that our fit is not completely reliable. First, the best-fit value of the absorption is 0 (although it is covariant with the blackbody temperature).

Third, stronger differences are seen at energies of 0.2–0.3 keV (see Figure 2). Some of these are too narrow to come from astrophysical sources and instead likely reflect problems in background subtraction (the low-energy background for the small-window data in particular can be significant and has substantial energy structure). Hence, it is difficult to interpret any residual structure there with respect to a blackbody.

### 3. DISCUSSION AND CONCLUSIONS

We have determined a reliable, statistically significant coherent spin-down solution for RX J0420. With this, only RX J1605.3+3249, which as yet has only a tentative detection of a periodicity, lacks a coherent solution (although in the cases of RX J2143.0+0654 and RX J0806.4−4123 spin-down was not well measured, and further observations are in progress). While the overall results of our timing program have been discussed at length in previous papers (overall energetics in vKK08; spectral implications in KvK09; evolutionary models in KvK09b), here we touch on some of the aspects that make RX J0420 unique and compare it to the other objects in its class.

First, while the timing properties (dipole magnetic field, \( \dot{E} \), characteristic age) of RX J0420 place it well within the INSs, RX J0420 has the shortest period by more than a factor of two. In the context of the magneto-thermal evolution model, this could be a consequence of a lower initial magnetic field, and thus less

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*References and notes are included as footnotes.*
dramatic early spin-down. RX J0420 also has the lowest current field, although it is not clear whether there is a good correlation between current magnetic field and period: RX J0806.4–4123 and RX J1343.0+0654 both have long periods but relatively weak fields. The magnetic field of RX J0420 is low enough that it would not be remarkable in a radio pulsar.

Second, the temperature of RX J0420 is the lowest of the INSs. Again, this might make sense if it is roughly the same age as the rest of the INSs but started with the lowest magnetic field. It would then have been heated the least and would come closest to the “pristine” cooling of a non-magnetic neutron star. In this context, it is interesting that RX J1856.5–3754 is cooler and less magnetized than RX J0720.4–3125 (1.5 versus 2.5 × 10^{13} G), while appearing the younger one by kinematic age (Kaplan et al. 2007; Tetzlaff et al. 2010, 2011). It would be interesting to measure the kinematic age of RX J0420 to compare it with the rest of the population.

To view the evidence for field decay in a different way, we show in Figure 3 the blackbody temperature versus characteristic age for pulsars and the INSs (see also Zhu et al. 2011). It is quite clear that the INSs are systematically a factor of 5–10 older in characteristic age for the same temperature. If instead one uses the kinematic age, however, one sees that the difference is much smaller (for the two sources for which kinematic ages are available). In the context of a picture in which the fields of INSs decayed, the main difference with pulsars induced by the initially much stronger field is thus that it leads to rapid initial spin-down and long present periods (and thus long characteristic ages); the current temperatures are not as strongly affected. Indeed, in the models of Pons et al. (2009), the heat generated by field decay is lost fairly rapidly.

Third, given both the low temperature and low magnetic field, RX J0420 largely follows the empirical-temperature–magnetic-field correlation from KvK09. As discussed there, the origin of this relation (evolutionary versus surface physics) or even its overall integrity in the face of new data are not clear. It does seem to form an upper limit to the possible magnetic field of an INS, and even the rotating radio transient J1819–1458 (possibly somewhat younger than the INSs, and with higher $\dot{E}$ as well) seems to roughly agree (based on McLaughlin et al. 2007).

Fourth, we did not confirm the tentative absorption feature found by H+04, although problems with the background subtraction meant we cannot refute it with confidence either. If it is true that RX J0420 has no broad X-ray absorption feature, it would join RX J1856.5–3754 (although as this object is often used for calibration assuming that it emits like a blackbody, it is difficult to set confident limits). These are the two INSs with the lowest temperatures and the lowest magnetic fields, suggesting some relation between the presence of absorption features (or their energy) and either temperature or field strength (although a direct correlation of energy with field strength seems excluded; KvK09). RX J0420 is also similar to RX J1856.5–3754 in its optical excess: both are reasonably well fit by Rayleigh–Jeanslike power laws, unlike the other INSs whose spectra are softer (Kaplan et al. 2011). It is possible that the optical/UV spectral index is related to the magnetic field, either directly through the magnetosphere (Tong et al. 2011) or indirectly through shifting spectral lines (Kaplan et al. 2011); in that case the similarity of RX J0420 and RX J1856.5–3754 would be natural.

Overall, our measurement firmly places RX J0420 as one of the INSs despite its short period and moves us significantly closer to having a complete sample of measured spin-downs for that population. There are still a number of open questions to be answered via X-ray and multi-wavelength observations. Primary among these is understanding the surface emission through consistent modeling of the spectra and light curves, and ideally with phase-resolved spectroscopy. Observations at optical/UV wavelengths of the pulsed emission could make significant improvements in our understanding, by tying the emitting areas at different wavelengths together and establishing the degree of surface inhomogeneity. Finally, further kinematic ages would help greatly in constraining the coupled evolution of magnetic field and temperature.

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