CONSTRAINING THE SPIN-DOWN OF THE NEARBY ISOLATED NEUTRON STAR RX J2143.0+0654

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ABSTRACT

Magnetic field estimates for nearby isolated neutron stars (INS; see Haberl 2007 and Kaplan 2008 for reviews) are a group of seven nearby (<1 kpc) neutron stars with low (~10^{-32} erg s^{-1}) X-ray luminosities and long (3-10 s) spin periods. When first discovered, a range of possible reasons for their long periods was suggested, with a corresponding range in magnetic field strengths of 10^{10}-10^{13} G: accretors (Koenck & Popov 1995; Wang 1997), long-period pulsars (Kulkarni & van Kerkwijk 1998; Kaplan et al. 2002; Zane et al. 2002), and middle-aged magnetars (Heyl & Kulkarni 1998). Field measurements can allow one to distinguish between these possibilities, and thus help understand the INS and their place in the greater neutron-star population. The magnetic field is also a necessary component of any realistic thermal emission models (Zane et al. 2004; Motch et al. 2003; Ho et al. 2007), required to interpret the surface emission and deduce radii and other properties of the INS.

Dipolar magnetic field strengths can be estimated from coherent timing solutions, and we used X-ray observations to derive such solutions for three INS, finding magnetic fields of (1 - 3) \times 10^{13} G (Kaplan & van Kerkwijk 2005ab, hereafter KvK05a,b; van Kerkwijk & Kaplan 2008, hereafter vKK08) also see (van Kerkwijk et al. 2007). This breakthrough is complemented by the discovery of broad absorption features at energies of 0.2 - 0.75 keV in the thermal (with bolometric luminosities of ~100 times the spin-down luminosity, the emission is certainly thermal) spectra of six of the seven INS. Assuming a pure hydrogen atmosphere, fields of 10^{13}-10^{14} G, and temperatures around 10^6 K, the absorption could be due to either proton cyclotron or transitions between bound states of neutral hydrogen. Intriguingly, for the two objects with both spectroscopic and spin-down magnetic fields, the agreement appeared to be good (van Kerkwijk & Kaplan 2007).

Here, we constrain the spin-down rate and hence magnetic field strength of the INS RX J2143.0+0654 (also 1RXS J214303.7+065419 or RBS 1774; hereafter RX J2143) with a series of dedicated XMM-Newton observations. RX J2143 was identified as a possible neutron star by Zampieri et al. (2001) on the basis of a soft thermal spectrum and the absence of an optical counterpart. Using XMM, Zane et al. (2005, hereafter Z+05) confirmed that the spectrum was soft and blackbody-like. They also found a broad absorption feature around 0.75 keV and identified a candidate 9^{13} G, which makes this object a particularly good test for models of the origin of the X-ray absorption and for understanding the INS population.

1. INTRODUCTION

The so-called isolated neutron stars (INS; see Haberl 2007 and Kaplan 2008 for reviews) are a group of seven nearby (<1 kpc) neutron stars with low (~10^{-32} erg s^{-1}) X-ray luminosities and long (3-10 s) spin periods. When first discovered, a range of possible reasons for their long periods was suggested, with a corresponding range in magnetic field strengths of 10^{10}-10^{13} G: accretors (Koenck & Popov 1995; Wang 1997), long-period pulsars (Kulkarni & van Kerkwijk 1998; Kaplan et al. 2002; Zane et al. 2002), and middle-aged magnetars (Heyl & Kulkarni 1998). Field measurements can allow one to distinguish between these possibilities, and thus help understand the INS and their place in the greater neutron-star population. The magnetic field is also a necessary component of any realistic thermal emission models (Zane et al. 2004; Motch et al. 2003; Ho et al. 2007), required to interpret the surface emission and deduce radii and other properties of the INS.

Dipolar magnetic field strengths can be estimated from coherent timing solutions, and we used X-ray observations to derive such solutions for three INS, finding magnetic fields of (1 - 3) \times 10^{13} G (Kaplan & van Kerkwijk 2005ab, hereafter KvK05a,b; van Kerkwijk & Kaplan 2008, hereafter vKK08) also see (van Kerkwijk et al. 2007). This breakthrough is complemented by the discovery of broad absorption features at energies of 0.2 - 0.75 keV in the thermal (with bolometric luminosities of ~100 times the spin-down luminosity, the emission is certainly thermal) spectra of six of the seven INS. Assuming a pure hydrogen atmosphere, fields of 10^{13}-10^{14} G, and temperatures around 10^6 K, the absorption could be due to either proton cyclotron or transitions between bound states of neutral hydrogen. Intriguingly, for the two objects with both spectroscopic and spin-down magnetic fields, the agreement appeared to be good (van Kerkwijk & Kaplan 2007).

Here, we constrain the spin-down rate and hence magnetic field strength of the INS RX J2143.0+0654 (also 1RXS J214303.7+065419 or RBS 1774; hereafter RX J2143) with a series of dedicated XMM-Newton observations. RX J2143 was identified as a possible neutron star by Zampieri et al. (2001) on the basis of a soft thermal spectrum and the absence of an optical counterpart. Using XMM, Zane et al. (2005, hereafter Z+05) confirmed that the spectrum was soft and blackbody-like. They also found a broad absorption feature around 0.75 keV and identified a candidate 9^{13} G, which makes this object a particularly good test for models of the origin of the X-ray absorption and for understanding the INS population.

2. OBSERVATIONS AND ANALYSIS

We observed RX J2143 11 times with XMM (Jansen et al. 2001) in 2007 and 2008, and focus here on the data taken with the European Photon Imaging Camera (EPIC) with pn and MOS detectors, all used in small window mode with thin filters (Table 1). All our observations, as well as the one from Z+05 (taken with the same settings), were processed with SAS version 8.0. We used epchain and enchain and selected source events from a circular region of 37.5'' radius with energies below 2 keV (where flares are negligible; the source is not detected above 2 keV). As recommended, we included only one-and-two-pixel (single and double patterns 0–4) events with no warning flags for pn, and single, double, and triple events (patterns 0–12) with the default flag mask for MOS1/2. We barycentered the event times using the Chandra X-ray Observatory position from Rea et al. (2007): α = 21^{h}43^{m}03^{s}38 and δ = +06°54′17″5 (J2000).
The best four solutions identified were the same as those found in the TOA analysis. The best-fit solution back to the 2004 observation: given its offset \( \Delta t = 1.233 \) days from the reference time \( t_0 \) of the above solution, the uncertainty on the cycle count is approximately \( \Delta \sigma \Delta t = 1.21 \) cycles. As a result, about six solutions are within \( \pm 2 \sigma \) of the best-fit solution, with implied spin-down values differing by \( \sigma_b/1.21 \) cycles = \( 1.7 \times 10^{-16} \) Hz s\(^{-1} \) (Figs. 1 and 2).

2.2. Spectral Analysis

We examined the EPIC-pn spectra of RX J2143 from our new data to verify whether the basic fits of \( Z+03 \) are still valid with our \( \sim 2.5 \) times longer total exposure time, and to look for possible long-term variability such as what de Vries et al. (2004) found for RX J0720-4.3125. (A full spectral analysis, including the EPIC-MOS and RGS data and phase-resolved fits, is in progress.) For our spectra, we used the same extraction regions as for the timing analysis, and an offset circular region with the same radius for the background (which is low). We created response files, and binned the spectral files such that the bin width was at least 25 eV (about one third of the spectral resolution) and the number of counts was at least 25.

We first fit our 11 new observations with an absorbed blackbody model over the 0.2–1.5 keV range (we use sherpA and the xsttabs absorption model of Wilms et al. 2000). The best-fit model had column density \( N_H = (2.28 \pm 0.09) \times 10^{20} \) cm\(^{-2} \), effective temperature \( kT_{BB} = 104.0 \pm 0.4 \) keV, and blackbody radius \( R_{BB} = 3.10 \pm 0.04 \) d/500 pc km, where the blackbody parameters are those measured by an observer at infinity. The results are similar to those of \( Z+03 \) for the 2004 data, with the slight offset likely resulting from changes in the EPIC calibration and from the inclusion of the MOS data (for the reprocessed 2004 EPIC-pn data, we find values much closer to those given above). The fit is reasonable, with \( \chi^2 = 469.0 \) for 431 dof. The resid-
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FIG. 2.—Possible timing solutions for RX J2143. Shown are $\chi^2$ values vs. spin-down rates $|\nu|$ (along the bottom axis) and dipole magnetic field (top axis) with 1 $\sigma$ uncertainties for solutions with $\nu < 0$ (circles) and $\nu > 0$ (squares), using only the data from 2007–2008 (8 dof). Also shown are the $\chi^2$ values for the $\nu < 0$ solutions incorporating the data from 2004 (9 dof; points), which have aliases with spacing $1.7 \times 10^{-16}$ Hz$^{-1}$ around each of the primary solutions (as labeled).

Table 2

| Quantity | Value |
|----------|-------|
| Dates (MJD) | 54,234–54,605 |
| $t_0$ (MJD) | 54,383.648930(2) |
| $\nu$ (Hz) | 0.1066044595(11) |
| $\nu$ ($10^{-16}$ Hz$^{-1}$) | $-4.6(20)$ |
| TOA rms (s) | 0.3 |
| $\chi^2$/dof | 6.0/8 |
| $P_r$ (s) | 9.429228889(9) |
| $P$ ($10^{-14}$ s s$^{-1}$) | $4.1(18)$ |
| $\tau_{\text{char}}$ (Myr) | $3.7$ |
| $B_{\text{dip}}$ ($10^{13}$ G) | $2.0$ |
| $E$ ($10^{30}$ erg s$^{-1}$) | $1.9$ |

Note.—Quantities in parentheses are the formal 1-$\sigma$ uncertainties on the last digit. $\tau_{\text{char}} = P/2P$ is the characteristic age, assuming an initial spin period $P_0 \ll P$ and a constant magnetic field; $B_{\text{dip}} = 3.2 \times 10^{12} \sqrt{PP}$ is the magnetic field inferred assuming spin-down by dipole radiation; $E = 3.9 \times 10^{46} P/P^3$ is the spin-down luminosity.

square spread of 3%, similar to the uncertainty on $A_{\text{abs}}$ in our fit to the actual data. The distribution of $\chi^2$ also conforms to expectations, with the $\chi^2$ including absorption never differing from the blackbody $\chi^2$ by more than 8.5 (compared to 61 for the real data). Thus, we confirm the detection of absorption at 0.75 keV by [Z+05]. Using the same continuum model but letting the absorption depth vary for each observation, we again find no statistically significant variability ($\Delta \chi^2 = 10$ for 11 fewer dof).

If we vary the energy of the absorption line $E_{\text{abs}}$ over the range 0.3–1.0 keV (avoiding the edges of the spectrum, where the continuum fit and the absorption are highly covariant), we find that, with one exception, only for $E_{\text{abs}} \approx 0.75$ keV is there significant absorption. Otherwise, $\Delta \chi^2 < 10$ and $A_{\text{abs}}$ is around 0. The one exception is a hint of absorption at 0.42 keV, which gives $\Delta \chi^2 = 15$ and $A_{\text{abs}} = 9.7\% \pm 2.3\%$. This detection is significant at the $\sim 3\sigma$ level given the 15 trials that we did (none of our 1000 simulations achieved such a high $\Delta \chi^2$). Such a line also improves the fit for the 2004 data, although not by a statistically significant amount ($\Delta \chi^2 = 4$). Confirmation of this with the EPIC-MOS and RGS data is ongoing.

3. DISCUSSION AND CONCLUSIONS

A large magnetic field of $\gtrsim 10^{14}$ G is inferred$^5$ for RX J2143 if one interprets the 0.75 keV absorption in its spectrum as arising from either proton cyclotron absorption ($1.4 \times 10^{14}$ G for a gravitational redshift $z = 0.3$) or ionization of hydrogen (even higher, as in [Z+05]; also see [van Kerkwijk & Kaplan 2007]). This scenario appeared to work well for RX J0720.4–3125 and RX J1308.6+2127, where those transitions could match the observed absorption features for magnetic fields of a

$^4$ Using an F test for finding lines is incorrect when the line model is located at the boundary of parameter space ([Protassov et al. 2002]). This, however, is not the case here since $A_{\text{abs}}$ can have either sign.

$^5$ This interpretation ignores the suppression of absorption lines due to vacuum resonance mode conversion in such strong magnetic fields; see [Ho & Lu 2004].
few times $10^{13}$ G, comparable to what was inferred from timing (van Kerkwijk & Kaplan 2007; Haberl 2007 and references therein). It also seemed consistent with the lack of features in RX J1856.5−3754, since that source has the weakest field (vKK08).

For RX J2143, though, the model breaks down: the required strong magnetic field is inconsistent with our timing measurements ($B_{\text{dip}} = 2 \times 10^{13}$ G) at the 10^−4 level (given $\Delta \chi^2 > 20$ for 3 parameters). In principle, the possible absorption feature at 0.4 keV may be easier to accommodate, although it still occurs at higher energy than the features seen in RX J0720.4−3125 and RX J1308.6+2127 while the magnetic field that we measure here is nominally weaker than the fields of those sources (Fig. 3). Furthermore, this leaves the 0.75 keV feature unexplained. It being a “harmonic” of the 0.4 keV line seems unlikely, as it is almost twice as strong, while one would expect harmonics to be significantly weaker (Pavlov & Panov 1976; G. G. Pavlov 2007, private communication). A better match may be possible with an atmosphere with helium or even heavier elements (Pavlov & Bezchastnov 2003; Hailey & Mori 2002; Z+03; Mori & Ho 2007); of course, in this case hydrogen must be absent, given the rapid gravitational settling time (Alcock & Illarionov 1980) and the small amount of hydrogen required to be optically thick (Romani 1987).

Geometry may offer a partial solution. The magnetic field that we infer from the spin-down rate is actually the true dipolar field strength times a function of the angle $\alpha$ between the magnetic and rotation axes. That function is $\sin \alpha$ in the traditional vacuum dipole model (Pacini 1967), which would give a large range of possible true field strengths. More modern analyses, however, give something more like $\sqrt{1 + \sin^2 \alpha}$ (Spitkovsky 2008), and thus a range of only 40%. Therefore, it seems unlikely that this can remedy the situation. Modeling of the pulse profile and phase-resolved spectroscopy has the potential to constrain the geometry (e.g., Zane & Turolla 2006), although X-ray polarimetry may be required for unambiguous results.

Turning to the properties of the INS as a whole, our result shows that not only do the INS cluster at long periods, but they are close in both axes of the $P - \dot{P}$ plane. The inferred magnetic fields for RX J1856.5−3754, RX J0720.4−3125, RX J1308.6+2127, and now RX J2143 are all within a factor of 2 of each other. Intriguingly, we also find a possible correlation between the effective temperature and magnetic field (Fig. 3) a similar realization was made by Pons et al. 2007 for a larger but less uniform sample, but see also Turolla et al. 2004 where the use of magnetic fields inferred from spectroscopy led to different conclusions). Whether or not RX J2143 fits this trend, however, will require an unambiguous timing solution.

A possible explanation for the clustering of the magnetic field strengths, and perhaps also the correlation with temperature, is that the fields were originally significantly stronger ($10^{14}$–$10^{15}$ G), and decayed. Such a scenario was originally proposed as a way to keep the INS hotter for much longer and thus make the natal population smaller (Heyl & Kulkarni 1998 also see Colpi et al. 2000). It is unlikely that field decay contributes much to the current thermal state, as the cooling and kinematic ages (from tracing the INS back to birth locations) agree well and the products of those ages and X-ray luminosities are about 100 times the energy currently in the dipole magnetic field, but decay may still have influenced the current field strengths. In particular, relatively fast field decay naturally leads to the tightly grouped periods and magnetic fields of the INS (Pons & Geppert 2007). It also naturally resolves why the spin-down ages $P/2\dot{P}$ (which assume constant magnetic field) are significantly longer than the kinematic ages: ~2 Myr versus 0.6 Myr (Kaplan et al. 2007; van Kerkwijk & Kaplan 2007; vKK08). Finally, field decay might also lead to a correlation between field and temperature, since both would be a function of age (note, however, that based on kinematic ages, RX J1856.5−3754 appears younger than RX J0720.4−3125 even though the former is colder: Kaplan et al. 2007). If field decay occurred, the INS would be the descendants of something like the magnetars, having had stronger fields (~$2 \times 10^{14}$ G, especially in the interiors) in the past, but with merely above average fields now. It could point to an evolutionary difference between the INS and the high-magnetic-field radio pulsars (e.g., Camilo et al. 2000) that inhabit the same region of the $P - \dot{P}$ diagram.

The correlation between temperature and field strength might also be evidence for something rather different, viz., surface physics. For a given magnetic field, as the surface cools, it is expected to condense (Ruderman 1974; Lai 2001). For iron, the condensation line is quite similar to the correlation we observe (Turolla et al. 2004; Medin & Lai 2007). From Fig. 3 one sees there is about a factor 2 difference in magnetic field, but this may just reflect the difference between the dipole and crustal fields, or between the true temperature and that inferred from a blackbody fit (indeed,
differences in the right sense are expected from atmosphere models; see [Zavlin & Pavlov 2002]. If condensation
indeed plays a role, it would help determine the surface composition (lighter elements do not condense
as easily), perhaps help understand the peculiar spectra of the INS, and, since a condensed surface may inhibit
the formation of a vacuum gap [Medin & Lai 2007], help explain the lack of radio emission from the INS (e.g.,
Kondratiev et al. 2008). It is less clear, however, what would keep the INS on the condensation line, or make
them evolve along it.

The above possibilities may well help understand what separates the INS from “normal” rotation-powered
middle-aged pulsars, which have a much wider range of magnetic field strengths in a comparable sample (e.g.,
Kaplan 2008). Understanding how the fields of these sources evolve and how this couples to the surface tem-
perature is also required to derive meaningful constraints from cooling measurements [Page et al. 2004]. To see
whether the fields are indeed clustered and/or correlated with temperature, will require measurements of other
sources, and refinement of that of RX J2143.

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REFERENCES

Alcock, C. & Illarionov, A. 1980, ApJ, 235, 534
Burwitz, V., Haberl, F., Neuhaus, R., Predel, P., Trümper, J., & Zavlin, V. E. 2003, A&A, 399, 1109
Camilo, F. et al. 2000, ApJ, 541, 367
Colpi, M., Geppert, U., & Page, D. 2000, ApJ, 529, L29
de Vries, C. P., Vink, J., Méndez, M., & Verbunt, F. 2004, A&A, 415, L31
Haberl, F. 2007, Ap&SS, 308, 181
Haberl, F. et al. 2004, A&A, 424, 635
Hailey, C. J. & Mori, K. 2002, ApJ, 578, L133
Heyl, J. S. & Kulkarni, S. R. 1998, ApJ, 506, L61
Ho, W. C. G., Kaplan, D. L., Chang, P., van Adelsberg, M., & Potekhin, A. Y. 2007, MNRAS, 375, 821
Ho, W. C. G. & Lai, D. 2004, ApJ, 607, 420
Jansen, F. et al. 2001, A&A, 365, L1
Kaplan, D. L. 2008, in American Institute of Physics Conference Series, Vol. 983, 40 Years of Pulsars: Millisecond Pulsars,
Magnetars and More, ed. C. Bassa, Z. Wang, A. Cumming, & V. M. Kaspi (New York: AIP), 331
Kaplan, D. L., Kulkarni, S. R., van Kerkwijk, M. H., & Marshall, H. L. 2002, ApJ, 570, L79
Kaplan, D. L. & van Kerkwijk, M. H. 2005a, ApJ, 628, L45
—. 2005b, ApJ, 635, L65
Kaplan, D. L., van Kerkwijk, M. H., & Anderson, J. 2007, ApJ, 660, 1428
Kondratiev, V. I., Burgay, M., Possenti, A., McLaughlin, M. A., Lorimer, D. R., Turolla, R., Popov, S., & Zane, S. 2008, in AIP
Conference Series, Vol. 983, 40 Years of Pulsars, ed. C. Bassa, Z. Wang, A. Cumming, & V. M. Kaspi (New York: AIP), 348
Konenkov, D. Y. & Popov, S. B. 1997, Astron. Lett., 23, 498
Kulkarni, S. R. & van Kerkwijk, M. H. 1998, ApJ, 507, L49
Lai, D. 2001, Rev. Mod. Phys., 73, 629
Medin, Z. & Lai, D. 2007, MNRAS, 382, 1833
Mori, K. & Ho, W. C. G. 2007, MNRAS, 377, 905
Motch, C., Zavlin, V. E., & Haberl, F. 2003, A&A, 408, 323
Pacini, F. 1967, Nature, 216, 567
Page, D., Lattimer, J. M., Prakash, M., & Steiner, A. W. 2004, ApJS, 155, 623
Pavlov, G. G. & Bezchastnov, V. G. 2005, ApJ, 635, L61
Pavlov, G. G. & Panov, A. N. 1976, Sov. Phys. JETP, 44, 300
Pons, J. A. & Geppert, U. 2007, A&A, 470, 303
Pons, J. A., Link, B., Miralles, J. A., & Geppert, U. 2007, Phys. Rev. Lett., 98, 071101
Protassov, R., van Dyk, D. A., Connors, A., Kashyap, V. L., & Siemiginowska, A. 2002, ApJ, 571, 545
Rea, N. et al. 2007, MNRAS, 379, 1484
Romani, R. W. 1987, ApJ, 313, 718
Ruderman, M. 1974, in IAU Symposium, Vol. 53, Physics of Dense Matter, ed. C. J. Hansen (Dordrecht: Kluwer), 117
Schwope, A. D., Hambaryan, V., Haberl, F., & Motch, C. 2005, A&A, 441, 597
Spitkovsky, A. 2008, in American Institute of Physics Conference Series, Vol. 983, 40 Years of Pulsars: Millisecond Pulsars,
Magnetars and More, ed. C. Bassa, Z. Wang, A. Cumming, & V. M. Kaspi (New York: AIP), 20
Turolla, R., Zane, S., & Drake, J. J. 2004, ApJ, 603, 265
van Kerkwijk, M. H. & Kaplan, D. L. 2007, Ap&SS, 308, 191
—. 2008, ApJ, 673, L163
van Kerkwijk, M. H., Kaplan, D. L., Durant, M., Kulkarni, S. R., & Paerels, F. 2004, ApJ, 608, 432
van Kerkwijk, M. H., Kaplan, D. L., Pavlov, G. G., & Mori, K. 2007, ApJ, 659, L149
Vink, J., de Vries, C. P., Méndez, M., & Verbunt, F. 2004, ApJ, 609, L75
Wang, J. C. L. 1997, ApJ, 486, L119
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
Zampieri, L. et al. 2001, A&A, 378, L5
Zane, S. & Turolla, R. 2006, MNRAS, 366, 727
Zane, S., Turolla, R., & Drake, J. J. 2004, Adv. Space Res., 33, 531
Zane, S. et al. 2002, MNRAS, 334, 345
—. 2005, ApJ, 627, 397
Zavlin, V. E. & Pavlov, G. G. 2002, in Neutron Stars, Pulsars, and Supernova Remnants, ed. W. Becker, H. Lesch, & J. Trümper,
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