SPECTRAL AND ROTATIONAL CHANGES IN THE ISOLATED NEUTRON STAR RX J0720.4–3125

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ABSTRACT

RX J0720.4–3125 is an isolated neutron star that, uniquely in its class, has shown changes in its thermal X-ray spectrum. We use new spectra taken with Chandra’s Low Energy Transmission Grating Spectrometer, as well as archival observations, to try to understand the timescale and nature of these changes. We construct lightcurves, which show both small, slow variations on a timescale of years, and a larger event that occurred more quickly, within half a year. From timing, we find evidence for a ‘glitch’ coincident with this larger event, with a fractional increase in spin frequency of $\sim 5 \times 10^{-8}$. We compare the ‘before’ and ‘after’ spectra with those from RX J1308.6+2127, an isolated neutron star with similar temperature and magnetic field strength, but with a much stronger absorption feature in its spectrum. We find that the ‘after’ spectrum can be represented remarkably well by the superposition of the ‘before’ spectrum, scaled by two thirds, and the spectrum of RX J1308.6+2127, thus suggesting that the event affected approximately one third of the surface. We speculate the effect reflects a change in surface composition caused by, e.g., an accretion episode.

1. INTRODUCTION

Among nearby neutron stars, seven show predominantly thermal emission, with inferred temperatures of $kT \approx 50$ to 100 eV. These so-called isolated neutron stars (INS) are thought to be young, $\lesssim 1$ Myr old, with the emission due to residual heat. Compared to similarly aged pulsars, they have much weaker non-thermal emission, longer, 3–10 s periods, and stronger, few $10^{13}$G magnetic fields (see Haberl 2006, Van Kerkwijk & Kaplan 2006 for recent reviews).

The INS have attracted much attention, in part because of the hope that the equation of state in the ultra-dense interior could be constrained using properties derived from their spectra, such as effective temperature, surface gravity, and gravitational redshift. Progress has been stymied, however, by difficulties in interpreting the spectra: at present, hydrogen, helium, and mid-Z elements, in states ranging from gaseous to condensed, all being considered (see, e.g., contributions to Page, Turolla, & Zane 2006).

A source that may elucidate matters is RX J0720.4–3125. This source was discovered with ROSAT, and has a 8.39 s period (Haberl et al. 1997). Initial XMM-Newton and Chandra spectra appeared to be featureless, blackbody-like (Paerels et al. 2001; Kaplan et al. 2003), similar to those of the brightest INS, RX J1856.5–3754 (e.g., Burwitz et al. 2001), but more detailed analysis uncovered a weak, broad absorption feature near 280 eV (Haberl et al. 2004a). Similarly broad (but stronger) features at energies from 200 to 700 eV were found in five other INS (Haberl et al. 2003, 2004b; Van Kerkwijk et al. 2004; Zane et al. 2005) and are generally interpreted as proton cyclotron or neutral-hydrogen transitions. For RX J0720.4–3125, either interpretation is consistent with the magnetic field strength $B \approx 2 \times 10^{13}$G inferred from timing (Kaplan & Van Kerkwijk 2005a, hereafter KvK05).

Unlike other INS, however, the spectrum of RX J0720.4–3125 changed (De Vries et al. 2004). The change could be described as an increase in temperature, from 86 to 94 eV, and an increase in equivalent width of the absorption feature, from $\sim 5$ to $70$ eV (Haberl et al. 2006, hereafter H06). The nature of the changes is unclear. De Vries et al. (2004) and Vink et al. (2004) find that they started gradually and then speeded up, and H06 find a recent, partial reversal. These authors interpret this as evidence for precession on a $\sim 7$ yr period.

In this Letter, we reconsider the timescale of the changes, investigate what changed, and offer an alternative interpretation. After describing the data we used in §2, we present lightcurves in §3 and update the timing solution of KvK05 in §4 finding evidence for a glitch at the time of the largest spectral change. We study the ‘before’ and ‘after’ spectra in §5 and suggest that only part of the surface changed. We discuss implications in §6.

2. OBSERVATIONS, REDUCTION, AND ANALYSIS

We used Chandra to observe RX J0720.4–3125 several times in 2005 and 2006, for $\sim 300$ ks total, taking spectra with the Low Energy Transmission Grating Spectrometer (LETG). For comparison, we analysed archival spectra taken in 2000 ($\sim 38$ ks) and 2004 ($\sim 36$ ks), as well as spectra of another INS, RX J1308.6+2127, taken in 2004 ($\sim 90$ ks).

For all observations, we extracted spectra following standard procedures (we used CIAO ver. 3.3 and CALDB ver. 3.2). We calibrated the spectra outside of CIAO: We subtracted the background, corrected for higher-order contributions using the observed counts and the Nov. 2004 effective areas, and calculated photon rates using the first-order effective areas. Note that we implicitly assume diagonal response matrices, thus ignoring the LETG line-spread function; this should be fine for spectra without sharp features, like ours. Finally, for timing purposes, we extracted barycentered source events (following KvK05).

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We augmented our data with archival XMM observations. For timing purposes, we extracted barycentered source events from all EPIC instruments (following KvK05), while for making lightcurves we extracted RGS spectra. The latter was done with rgsproc (XMMASAS ver. 7.0), which was also used to produce flux-calibrated spectra (ignoring, like for LETG, the line-spread function). We note that XMMASAS ver. 7.0 includes corrections for the changing long-wavelength sensitivity of RGS,5 which has influenced previous analyses (see §3).

3. TIME SCALES OF THE SPECTRAL CHANGE

To determine the timescale on which the spectral changes occurred, we used the LETG and RGS spectra to produce lightcurves in eight wavelength bands (Fig. 1). Broadly, these confirm previous results (see §1): as time passed, the flux increased at wavelengths $\lambda \lesssim 25\,\AA$, and decreased in the range $35 \lesssim \lambda \lesssim 55\,\AA$, presumably because the absorption feature deepened. However, with the new RGS long-wavelength efficiencies, the evidence for a decrease in $25–36\,\AA$ flux before 2003 has largely disappeared (but the first LETG and RGS observations have become discrepant, suggesting some calibration issues remain).

Figure 1 shows that most of the change occurred rapidly, in between the 2003 May and 2003 October XMM observations.

5 See XMM-SAS ver. 7.0 and XMM-CCF-REL-216 release notes.

### TABLE 1

| Instrument | ID | Date (Day of MJD) | Exp. (ks) | Counts | TOA (MJD) |
|-----------|---|------------------|---------|-------|------------|
| PN        | 986-S3 | 2005 Apr 28 | 52.0 | 309204 | 53488.675603(3) |
| MOS1      | 986-S1 | 2005 Apr 30 | 41.1 | 51871 | 53488.601306(8) |
| MOS2      | 986-S2 | 2005 Apr 30 | 41.2 | 54046 | 53488.601296(8) |
| HRC       | 5582 | 2005 Jun 01 | 69.7 | 903822 | 53522.937973(12) |
| PN        | 1060-S3 | 2005 Sep 23 | 51.0 | 284343 | 53636.300148(4) |
| MOS1      | 1060-S1 | 2005 Sep 23 | 36.9 | 50933 | 53636.202428(8) |
| MOS2      | 1060-S2 | 2005 Sep 23 | 36.9 | 51231 | 53636.202347(8) |
| HRC       | 6369 | 2005 Oct 08 | 26.0 | 409201 | 53652.085952(2) |
| PN        | 1086-S3 | 2005 Nov 12 | 38.0 | 268168 | 53687.171885(4) |
| MOS1      | 1086-S1 | 2005 Nov 12 | 39.5 | 56534 | 53687.158660(8) |
| MOS2      | 1086-S2 | 2005 Nov 12 | 39.5 | 56292 | 53687.158665(7) |
| HRC       | 7243 | 2005 Dec 14 | 17.1 | 241664 | 53718.146289(25) |
| PN        | 1060-S3 | 2005 Dec 15 | 16.2 | 227541 | 53719.808713(22) |
| MOS1      | 1060-S1 | 2005 Dec 15 | 17.1 | 249521 | 53720.770160(30) |
| MOS2      | 1086-S2 | 2005 Dec 16 | 14.1 | 194582 | 53721.915718(30) |
| HRC       | 7251 | 2006 Feb 09 | 10.6 | 160780 | 53775.350898(12) |

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Note. — A log of earlier observations and corresponding times of arrival can be found in Kaplan & van Kerkwijk (2005).

To examine broad-band changes, we integrated the LETG fluxes in the 10–80 Å range (0.155–1.25keV), finding totals of 0.97, 1.06, 1.04, 1.02, 1.04, and 1.02 erg s$^{-1}$ cm$^{-2}$ for the six observations, respectively (with $\sim 2\%$ uncertainty).

Before and after, there are slower variations, with those before in the same sense as the rapid change, and those after in the opposite one. This is consistent with inferences from PN data by H06.

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5 See XMM-SAS ver. 7.0 and XMM-CCF-REL-216 release notes.
TABLE 2

| Quantity                  | Excl. ROSAT | All Data |
|---------------------------|-------------|----------|
| Spindown only             |             |          |
| \( t_0 \) (MJD)           | 53010.263566(7) | 53010.2635626(6) |
| \( \nu \) (Hz)            | 0.11917366979(12) | 0.11917366954(11) |
| \( \dot{\nu} \) (Hz s\(^{-1}\)) | \(-9.74(4) \times 10^{-16}\) | \(-9.88(13) \times 10^{-16}\) |
| TOA rms (s)               | 0.26        | 0.29     |
| \( \chi^2/dof \)          | 77.6/46=1.69 | 150.8/49=3.08 |
| Spin-down + Glitch        |             |          |
| \( t_0 \) (MJD)           | 53010.2635686(10) | 53010.2635667(10) |
| \( \nu \) (Hz)            | 0.1191736716(9) | 0.1191736716(9) |
| \( \dot{\nu} \) (10^{-15} Hz s\(^{-1}\)) | \(-1.04(3)\) | \(-1.04(3)\) |
| \( t_1 \) (MJD)           | 52817(61)   | 52866(73) |
| \( \Delta \nu \) (nHz)    | 5.7(17)     | 4.1(12)  |
| \( \Delta \dot{\nu} \) (10^{-17} Hz s\(^{-2}\)) | \(-1(4)\) | \(-4(3)\) |
| TOA rms (s)               | 0.15        | 0.24     |
| \( \chi^2/dof \)          | 37.0/43=0.86 | 45.1/46=0.98 |

Note. — The parameters determine the cycle count plus phase via \( \phi(t) = \nu(t-t_0) + \Delta \nu \phi(t) \), where \( \Delta \nu \phi(t) = -\Delta \nu(t - t_1) - \frac{1}{2} \Delta \dot{\nu}(t - t_1)^2 \) for \( t < t_1 \) in the glitch model and otherwise. For all fits, a 0.11 s systematic uncertainty has been added in quadrature to the times of arrival (TOAs), and the uncertainties quoted are twice the formal 1\( \sigma \) values.

the simple spin-down model. This improves the fit drastically (Fig. 1): to get \( \chi^2_{\text{red}} \approx 1 \), a systematic error term of only 0.11 s is required. Intriguingly, the best-fit glitch time coincides with the period of the greatest spectral change.

In Table 2 we list parameters for the simple spin-down and the glitch models. We try solutions both with and without the ROSAT data (which have much less secure cycle counts); in either case, the change in \( \nu \) is significant, but that in \( \dot{\nu} \) is not.

The addition of a glitch improves the fit, but also adds complexity. To evaluate the significance of the improvement, we tried two other ways of adding complexity. First, we included higher-order frequency derivatives, but found a similarly improved fit required eighth order (i.e., six additional parameters). Second, motivated by the suggestion of H06 of Van Kerkwijk & Kaplan 2006). The result did not seem to be associated with only a small change in temperature (from \( kT \approx 86 \) to 94 eV, H06)? Second, motivated by the suggestion of H06 of Van Kerkwijk & Kaplan 2006). The result did not seem to be associated with only a small change in temperature (from \( kT \approx 86 \) to 94 eV, H06)?

The comparison of the spectra raises two main questions. First, for RX J0720.4–3125, how can the appearance of a pronounced absorption feature be associated with only a small change in temperature (from \( kT \approx 86 \) to 94 eV, H06)? Secondly, motivated by the suggestion of H06 of Van Kerkwijk & Kaplan 2006). The result did not seem to be associated with only a small change in temperature (from \( kT \approx 86 \) to 94 eV, H06)?

FIG. 2.—Calibrated LETG spectra. The spectrum of RX J0720.4–3125 from 2000 (red open circles) is well described by an absorbed black-body \( N_H = (1.55 \pm 0.1) \times 10^{20} \text{cm}^{-2}, kT = 83.3 \pm 1.1 \text{eV, and } r/d = 0.0189 \pm 0.0008 \text{km} \text{pc}^{-1} \) (dashed red curve). The average post-2003 spectrum (magenta filled circles) could be a superposition of spectra from unchanged and changed parts of the surface. As an indication, a close to maximum contribution by the unchanged spectrum is indicated (magenta, dotted line). The residual (blue, wiggly curve, offset down by 0.1 unit for clarity) is remarkably similar to the spectrum of RX J1308.6+2127 (green squares, scaled by a factor 1.2). For all spectra, the 40–44 Å range is less reliable, because of strong instrumental carbon absorption.

ond, why is the absorption feature in RX J1308.6+2127 much stronger than that in RX J0720.4–3125 (in either state)?

Of these two questions, we believe the answer to the second may be simple: that not the whole but only part of the surface changed. If so, then the ‘after’ spectrum contains a contribution from unchanged parts that emit the cooler, nearly featureless ‘before’ spectrum. Hence, the spectrum from the changed part should be hotter and should have a stronger line than one would infer from the average.

We do not know the relative contribution of the ‘before’ spectrum, but an upper limit of \( \sim 70\% \) is set by the requirement that it does not exceed the ‘after’ spectrum at any wavelength (set by the 35–40 Å region; Fig. 2). For a contribution near this limit, the absorption feature in the changed parts of the surface would be very strong, just as observed in RX J1308.6+2127. Indeed, if we subtract the ‘before’ spectrum, scaled by two thirds, from the ‘after’ spectrum, the residual is remarkably similar to the spectrum of RX J1308.6+2127 (see Fig. 2). This is confirmed by the EPIC-pn data (Mori et al., in preparation).

5. NATURE OF THE SPECTRAL CHANGE

The lightcurves show that most of the spectral change in RX J0720.4–3125 took place in 2003. In Fig. 2, we show the LETG spectrum from 2000, taken before this time, as well as the average of all LETG spectra taken after 2003 (the further small changes in 2004 and 2005 [Fig. 1] would not be noticeable in Fig. 2). For comparison, we also show the LETG spectrum of RX J1308.6+2127, which is very similar to RX J0720.4–3125 in its inferred temperature, extinction, and magnetic field strength \( (kT \approx 100 \text{eV, } N_H \approx 2 \times 10^{20} \text{cm}^{-2}, \text{Schwope et al. 2006) } B \approx 3 \times 10^{13} \text{G, Kaplan & van Kerkwijk 2005b}) \).

The comparison of the spectra raises two main questions. First, for RX J0720.4–3125, how can the appearance of a pronounced absorption feature be associated with only a small change in temperature (from \( kT \approx 86 \) to 94 eV, H06)? Second, motivated by the suggestion of H06 of Van Kerkwijk & Kaplan 2006). The result did not seem to be associated with only a small change in temperature (from \( kT \approx 86 \) to 94 eV, H06)?

6. RAMIFICATIONS

We have found that most of the spectral variations in RX J0720.4–3125 occurred on a short, less than half-a-year timescale, and that, coincident with this, there likely was an increase in spin frequency. We also showed that the ‘after’ spectrum could be reproduced if one third of the emission changed from the blackbody-like ‘before’ spectrum to something similar to the emission of RX J1308.6+2127, and we suggested only part of the visible surface changed. Here, we will interpret these findings assuming an impulsive event (see H06 for a discussion in terms of precession). As the observations show evidence for a reversal, we need to address not
only the nature and cause of the change, but also how it can be undone.

It is difficult to understand the cause without knowing the composition and state at the photosphere (§1). The order-of-magnitude increase in strength of the absorption feature suggests, however, that a new species became dominant, due to a change in ionisation balance, state (e.g., from condensed to gaseous), or composition.

In principle, a temperature change could affect the ionisation balance or state, and one could envisage heating due to a sudden energy release associated with, e.g., a glitch, and subsequent cooling on a timescale set by the release depth. However, the average observed flux before and after the event differs by only ~5%. Even if due to only one third of the surface, the implied increase in effective temperature is at most 4% ([H06 find a 6% change in average temperature from spectral fits, but this may simply reflect that a model of a blackbody with a gaussian absorption line is not realistic.] With such a small change, it is not clear the atmosphere and spectrum could change so drastically.

An easier explanation for the strengthening of the absorption feature would be a change in composition, e.g., due to an accretion episode. Such a change could also lead to a small increase in effective temperature, since heat conduction is faster for lighter elements (e.g., [Potekhin et al. 2003].

But how to undo the change? For hydrogen, there is a possible mechanism ([Chang, Arras, & Bildsten 2004]: for B ≈ 2 × 10^{13} G and T_{eff} ≈ 10^4 K, hydrogen will be burnt diffusively on carbon in ~200 × 10^3 yr (where 3H1 = 10\sqrt{10} G cm^2 is the hydrogen column density), with substantial uncertainty due to the composition of the underlying layers. A thin hydrogen layer, superposed on a condensed surface, has been invoked by [Motch, Zavlin, & Haberl 2003] and [Ho et al. 2006] to explain the featureless spectra of some INS. For RX J0720.4–3125, it would imply a very thin hydrogen layer before the change, and a thicker one on parts of the surface afterwards.

Among the two possibilities mentioned above – a glitch in the neutron-star crust and an accretion episode – the former would most naturally explain the timing results; indeed, the fractional increase in spin frequency of ∆Ω/Ω = 5 × 10^{-8} would not be unusual for an older radio pulsar (e.g., [Janssen & Stappers 2006]). Also for magnetars, glitches are observed, as well as slow changes on timescales of years (see [Kaspi 2006 for a review]). The glitch could release some energy, causing a temperature increase that depends on the release depth (e.g., [Hui & Cheng 2004] and references therein). In addition, it could induce magnetospheric currents, which could produce hydrogen and helium on the surface by spallation (as suggested for RX J1856.5–3754 by [Ho et al. 2006]).

Accretion would naturally lead to a change in composition, as well as, by its associated angular momentum, a change in spin. Matter could originate in an asteroid or comet belt such as has been invoked to explain timing noise, nulling and other pulsar properties by [Cordes & Shannon 2006]. If accretion started due to a collision between asteroids, low-rate accretion of smaller debris could perhaps cause the slower changes. The observed frequency change requires an accreted mass of ~10^{-10}–10^{-11} g, depending on accretion regime and properties of accreting matter (large bodies accreting directly onto the star, small grains destructed and ionized before reaching the Alfvén surface, etc.). The accretion would result in an energy of ~10^{39}–10^{41} erg being released in a relatively short time, hence a high luminosity. We have checked the RXTE All-Sky Monitor (ASM) data in 2003 May–October and found no emission from RX J0720.4–3125; however, given the low ASM duty cycle, a short-lived (~10 ks) event could easily be missed.

In future, the above ideas – as well as the alternative suggestion of precession ([H06] can be tested. For instance, both give different predictions for future timing. Generally, if hydrogen appeared on the surface (or hydrogen-covered parts became visible), the optical flux should perhaps have increased, yet it changed by ~10% ([Kaplan, van Kerkwijk, & Anderson 2007]. Also, if the composition changed locally, e.g., near a magnetic pole, matter might diffuse outwards, perhaps leading to further slow changes. If so, one would also expect that the pulse profile evolved, perhaps being more sharply peaked, especially at high energies, shortly after the event. From the PN data, this indeed appears to be the case (Mori et al., in preparation).

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