TIMING ANALYSIS OF THE ISOLATED NEUTRON STAR RX J0720.4-3125

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Abstract

We present a combined analysis of XMM-Newton, Chandra and Rosat observations of the isolated neutron star RX J0720.4-3125, spanning a total period of ~ 7 years. We develop a maximum likelihood periodogramme based on ΔC-statistic and maximum likelihood method, which are appropriate for sparse event lists. As an a posteriori check, we have folded a further BeppoSAX-dataset with the period predicted at the time of that observation, finding that the phase is consistent.

The study of the spin history and the measure of the spin-down rate are of extreme importance in understanding the mechanism powering RX J0720.4-3125. The value of the period P, here measured for the first time, is ~ 10^{-14} s/s and can not be explained in terms of propeller or torque from a fossil disk. When interpreted in terms of dipolar losses, it gives a magnetic field of B ~ 10^{13} G, making also implausible that the source is accreting from the underdense surroundings. We also find unlikely that the field decayed from a much larger value (B ~ 10^{15} G in the past, as expected in the “old magnetar” interpretation) since this scenario predicts a source age of ~ 10^4 yrs, too young to match the (low) observed X-ray luminosity. The observed properties are more compatible with a scenario in which the source is ~ 10^6 yrs old, and its magnetic field has not changed substantially over the lifetime.

Key words: Stars: neutron — stars: oscillations — pulsars: general — magnetic fields.

1. Introduction

RX J0720.4-3125 is a nearby, isolated neutron star (NS) detected by ROSAT during a Galactic plane survey (Haberl et al. 1997) and recently re-observed with XMM-Newton on 2000 May 13 (Paerels et al. 2001; Cropper et al. 2001) and 2001 November 21. The source exhibits all the common characteristics of the other six ROSAT NS candidates (hereafter dim NSs, see Treves et al. 2000 for a review): a blackbody-like spectrum with kT ~ 80 eV; a large X-ray to optical flux ratio; a low X-ray luminosity, L_X ~ 10^{30} – 10^{31} erg/s; a low column density and no evidence for a binary companion. In addition, RX J0720.4-3125 is pulsating with a period P ~ 8.4 s.

Until a few years ago, dim NSs were thought to constitute a class stand alone and two mechanisms were proposed for their emission: either accretion from the interstellar medium onto an old NS or release of thermal radiation from a younger, cooling object. More recently, based on the similarity of the periods, it has been suggested a possible evolutionary link between dim NSs, anomalous X-ray pulsars (AXPs), and soft gamma-ray repeaters (SGRs). Two kind of “unified” scenarios have been then proposed. In the first one, the three classes of objects are powered by dissipation of a decaying, superstrong magnetic field (B ~ 10^{14} – 10^{15} G). In this case dim NSs are the descendants of SGRs and AXPs, and RX J0720.4-3125 may be one of the closest old-magnetars. Alternatively, all the three classes may contain NSs with lower (canonical) magnetic field (B ~ 10^{12} G) endowed by a fossil disk (Alpar et al. 2001). In this case dim NSs in the propellor phase would be the progenitors of AXPs and SGRs, the latter having entered an accretion phase.

Recently, Paerels et al. (2001) presented XMM-Newton spectra of RX J0720.4-3125. The absence of electron or proton cyclotron resonances in the RGS range excluded magnetic fields of B ~ (0.3 – 2) x 10^{11} G and (0.5 – 2) x 10^{14} G (see Zane et al. 2001). Based on the same XMM-Newton observation, Cropper et al. (2001) presented the pulse-shape analysis. They derived an upper limit on the polar cap size, showing that an emitting region larger than ~ 60° – 65° can be rejected at a confidence level of 90%. Whatever the mechanism, the X-ray emitting region is therefore confined to a relatively small fraction of the star surface. They also found that the hardness ratio is softest around the flux maximum. The same has been later discovered by Perna et al. (2001) in some AXPs. Cropper et al. (2001) suggested two possible explanations for this effect: either radiation beaming (as in their best-fitting model) or the presence of a spatially variable absorbing matter, co-rotating in the magnetosphere. The latter may be indeed the case if the star is propelling matter outward (Alpar et al. 2001).

Further information about the nature of this puzzling source can be obtained by the spin history. Magnetars will spin-down at a rate P ~ 10^{-11} (B/10^{14} G)^2/P ss^{-1}, due to magneto-dipolar losses. The preliminary measure of P published by Haberl et al. (1997) for RX J0720.4-3125 is uncertain to a considerable large value, and does not...
even allow spin-up and spin-down to be discriminated. An accurate determination of $\dot{P}$ is therefore crucial, as well a tracking of the spin history of the source. Here we present a combined analysis of XMM-Newton, Chandra and Rosat data, spanning a period of ~ 7 years. For all details we refer to the paper Zane et al. (2002).

2. Timing Analysis

The different observations used in our analysis are shown in table 1; the major datasets are from the two XMM observations and from the 1996 Nov. 3 Rosat pointing, while the 1998 Rosat and the Chandra observations are valuable by nature of their several day durations. Our data originate from instrumentation with widely differing sensitivities: typical count rates vary from 1 count every ~ 3 s for Rosat HRI to ~ 6 counts/s for XMM-Newton PN. However, none of these count rates is sufficiently high for a normal distribution of counts to be expected, thus standard discrete Fourier Transforms are not directly applicable. For sparse data and event list data, we used instead Rayleigh Transform (i.e. de Jager 1991, Mardia 1972). It is also crucial for us to define precisely the confidence intervals to the derived quantities, in particular the period $P$. We do this by constructing MLP (maximum likelihood periodogrammes) which make no assumptions on data distribution, and using the $\Delta C$-statistics (Cash 1979). The uncertainty in the period and the $\chi^2$ can be read directly from the $y$-axis of the MLP (see figure 1).

Table 1. The ROSAT, Chandra and XMM-Newton observations of RX J0720.4-3125 used in this analysis. The entry in the third column is the effective exposure.

| Date       | Instrument | Eff. Exp. (s) | Label |
|------------|------------|---------------|-------|
| 1993 Sep 27| Rosat PSPC | 3221          | R93   |
| 1996 Apr 25| Rosat HRI  | 3566          | R96a  |
| 1996 May 7 | Rosat HRI  | 3125          | R96b  |
| 1996 Sep 27| Rosat HRI  | 1409          | R96c  |
| 1996 Nov 3 | Rosat HRI  | 33569         | R96d  |
| 1998 Sep 27| Rosat HRI  | 3566          | R98   |
| 2000 Feb 1 | Chandra HRC-S | 37635       | Ch00  |
| 2000 May 13| XMM MOS1   | 61648         | X00a  |
|            | MOS2       | 61648         |       |
|            | PN         | 62425         |       |
| 2000 Nov 21| XMM MOS1   | 17997         | X00b  |
|            | MOS2       | 17994         |       |
|            | PN         | 25651         |       |
| 1997 Mar 16| SAX LECS   |               | S97   |

We first performed an MLP assuming $\dot{P} = 0$ on each of the longer pointing: R93, R96d, X00a, X00b (figure 1). There is no ambiguity in the period determinations and a linear least square fit using the 68% formal errors in the MLP gives $P_0 = 8.39113 \pm 0.00011$ s, $P = 0.0 \pm 5.5 \times 10^{-13}$ s/s (here and in the following $P_0$ is referenced to the start of the R93 run). This upper limit on $\dot{P}$ permits an unambiguous determination of the peaks in the Ch00 and R98 power spectra. Adding these to the linear square fit gives $P_0 = 8.39107 \pm 0.00005$ and $P = 2.7 \times 10^{-13} \pm 2.5 \times 10^{-13}$. The 68, 90 and 99% confidence intervals are shown in figure 2, as well the 68 and 90% intervals derived from...
X00a. With the improved \((P_0, \dot{P})\) values, we performed an MLP on the combined R93 and R96 datasets. As a result, the confidence contour break up into small region (aliases) in the \((P_0, \dot{P})\) plane (see zoom in figure 2). With this further restriction, we finally do the MLP on all data. We derive two pairs of values \((P_0, \dot{P})\) which cannot be further discriminated between on statistical grounds (table 2).

| Label | \(P_0(s)\) | \(\dot{P}(s/s)\) | \(\Delta \chi^2\) |
|-------|-------------|-----------------|----------------|
| (1)   | 8.39109273  | \(5.409 \times 10^{-14}\) |                |
| (2)   | 8.39109148  | \(3.749 \times 10^{-14}\) | 1.3            |

Figure 3. The 68\% and 90\% MLP contours for \(P_0\) and \(\dot{P}\) to the complete dataset except for the R98 data, for the two solutions (1) and (2).

Figure 4. The datasets folded on the \((P_0, \dot{P})\) solution (1) (left) and (2) (right).

Figure 3. The 68\% and 90\% MLP contours for \(P_0\) and \(\dot{P}\) to the complete dataset except for the R98 data, for the two solutions (1) and (2).

3. Discussion

The refined value of \(\dot{P}\) reported here is consistent with, but two orders of magnitude lower than the extrema of the range reported by Haberl et al. (1997). The first implication is that RX J0720.4-3125 is unlikely to be spinning down under propeller torques (Alpar 2001). In this case, under the assumption that the X-ray luminosity of the source \((L_X \approx 2 \times 10^{31} \text{erg cm}^{-2} \text{s}^{-1})\), where \(d_{100} = d/100\) pc and \(d\) is the distance, Haberl et al. (1997) is supplied by energy dissipation, it should be:

\[
2 \times 10^{-11} d_{100}^2 \leq \dot{P} \leq 2 \times 10^{-9} d_{100}^2 \text{s}\text{s}^{-1}.
\]

The scenario is still consistent with the spin-down recently measured for RBS 1223 (Hambaryan et al. 2001), but the value of \(\dot{P}\) reported here for RX J0720.4-3125 is still considerable. The other plausible mechanism which may account for such large and stable value of \(\dot{P}\) is magnetic breaking. For a dipolar magnetic field \(\dot{P} \approx 10^{-15} (B/10^{12} \text{G})^2 / \text{P s/s}\), which gives \(B = 2.13 \times 10^{13} \text{G}\). A scenario in which this source is powered by accretion from the interstellar medium must be therefore ruled out: for the present values of \(P\) and \(B\) the co-rotating magnetosphere will prevent the incoming material to penetrate below the Alfven radius.

\[\text{Here and in the following we specify the discussion to solution (1) of table 2.}\]
| B-Decay Mechanism                  | $B_0$  | $\Delta t_{\text{sd}}$ (years) |
|-----------------------------------|--------|-------------------------------|
| Hall Cascade                      | 119.2  | $4.5 \times 10^4$             |
| Ambipolar diffusion, irrotational mode | 1.9    | $3.3 \times 10^6$             |
| Ambipolar diffusion, solenoidal mode | 4.1    | $1.6 \times 10^6$             |

Table 3. Predicted source age and primordial field for three different mechanisms of decay, simulated as in Colpi et al. 2000. The present values of $P$ and $P$ are those of solution (1) in table 3. In all cases, the source is assumed to be born with $P = 1$ ms.

The corresponding spin-down age is $t_{\text{sd}} = \dot{P}/(2P) \sim 2.48 \times 10^6$ yr, which, given the numerous uncertainties, is marginally compatible with that inferred by the cooling curves (a few $10^6$ yrs for a surface temperature of $\sim 80$ eV, e.g. Kaminker et al. 2001a, Kaminker et al. 2001b, Schaab et al. 1999, Schaab et al. 1999). The discrepancy is less significant if we notice that what we are probably observing in the X-ray is a region of limited size which is kept hotter than the average star surface, as inferred by the analysis of the pulse-shape (Cropper et al. 2001).

On the other hand, $t_{\text{sd}}$ is representative of the true age of the source only in the case in which the magnetic field remained almost constant during the star evolution. The same condition applies for the validity of the cooling curves mentioned above, which do not include the extra input of energy released in the neutron star in case of field decay. It is therefore of fundamental importance to address the field evolution. There are three mechanisms which are typically proposed for inducing field-decay: ambipolar diffusion in the solenoidal or irrotational mode and Hall cascade (Goldreich & Reisenegger 1992, Heyl & Kulkarni 1998, Colpi et al. 2000). By using the simplified expressions of Colpi et al. (2000) for the decay laws, we have estimated the source age and the value of the magnetic field at the birth of the neutron star, $B_0$ (table 3).

As we can see, allowing for a mechanism involving very fast decay, such as the Hall cascade, we find that the source is now $\sim 4 \times 10^4$ yr old, and is born with a superstrong field $B_0 \sim 10^{15}$ G. Such a young age is only marginally compatible with the absence of a remnant and, more important, is not compatible with the low observed X-ray luminosity. Underluminous models have been presented by Kaminker et al. (2001a) who accounted for the enhanced neutrino cooling in presence of strong neutron superfluidity. These solutions may match an age of $\sim 10^4$ yrs for RX J0720.4-3125, but, as discussed by the same authors, they must probably be rejected since they fail in the comparison with observational data of a sample of other neutron stars.

On the other hand, both mechanisms involving ambipolar diffusion predict a magnetic field quite stable over the source lifetime and close to the actual value. Accordingly, the predicted age is $\sim 10^6$ years in all cases, close to $t_{\text{sd}}$. Below $\sim 10^{14}$ G the cooling curves are not significantly influenced by decay through ambipolar diffusion (Heyl & Kulkarni 1998), thus, as in the case of constant $B$ discussed above, the scenario is compatible with the observed luminosity. The larger age is also compatible with the absence of a remnant.

If our conclusions are valid, the connection between dim INS and AXPs is not so obvious. RX J0720.4-3125 has a strong, but not superstrong, field which is compatible with those of the canonical radio-pulsars which have passed the death line. On the other hand, having excluded accretion, what mechanism causes an X-ray emission concentrated in a fraction of $\sim 60\%$ of the star surface remain a mystery, as well the related question about the validity of using the observed blackbody temperature to locate the source in the cooling diagram. The variation of the surface cooling temperature with the latitude predicted so far for strong fields (Greenstein & Hartke 1983, Possenti et al. 1996) is too smooth to explain the (relatively) small size of the emitting region, and different explanations are required.

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