The Be Phenomenon in Early-Type Stars, IAU Colloquium 175
ASP Conference Series, Vol. 214, 2000
M. A. Smith, H. F. Henrichs, and J. Fabregat, eds.

Evidence for Magnetic Field Decay in the Slowest Known Be/X-ray Pulsars X Per and RX J0146.9+5121

X.-D. Li and Z.-R. Wang

Department of Astronomy, Nanjing University, Nanjing 210093, P. R. China

Abstract. We argue that the slowest known Be/X-ray pulsars X Per and RX J0146.9+5121 currently possess relatively weak ($\lesssim 10^{12}$ G) magnetic fields. Unless these pulsars were born rotating very slowly (initial periods longer than tens of seconds), in order to explain their long spin periods ($\sim$ 835 and $\sim$ 1412 s, respectively), they must have had magnetic fields stronger than a few 10^{13} G; that is, their magnetic fields must have decayed.

1. Introduction

Evolution of magnetic fields in neutron stars has been long debated since the discovery of radio pulsars. It is generally believed that the magnetic fields in isolated neutron stars decay with a characteristic timescale more than 20 Myr, while the low magnetic fields ($\lesssim 10^{10}$ G) in binary and millisecond radio pulsars, as well as in neutron stars in low-mass X-ray binaries (LMXBs), are related to mass transfer in binary evolution (Bhattacharya & van den Heuvel 1991 for a review). Although the detailed mechanism for accretion-induced field decay remains unclear, and controversies still exist concerning the relation between field decay and the amount of the accreted mass (e.g., Wijers 1997). Here we present evidence indicating that field decay has occurred in the slowest known Be/X-ray pulsars X Per and RX J0146.9+5121.

2. Properties of the slow Be/X-ray pulsars X Per and RX J0146.9+5121

The X-ray sources X Per and RX J0146.9+5121 have the longest known spin periods ($\sim$ 835 s and $\sim$ 1412 s respectively) of a neutron star in a Be/X-ray binary. Their X-ray characteristics are notably different from those of other Be/X-ray systems (Haberl et al. 1998 and references therein): (1) They are the least variables of high-mass X-ray binaries in the X-ray region, showing persistent low-level X-ray luminosities $\sim 10^{34}\,\mathrm{erg\,s^{-1}}$ in the $2-10$ keV band after their outbursts. It appears that their X-ray luminosities are not directly related to the behavior of the optical counterparts. (2) Their X-ray spectra are consistent with a power law with a cutoff at $2-5$ keV, which is relatively low compared to the $10-20$ keV cutoff energies in typical binary X-ray pulsars (Nagase 1989). There is no evidence for the $6.4-6.7$ keV iron Kα line, often

https://doi.org/10.1017/S0252921100056839 Published online by Cambridge University Press

found in high-mass X-ray binaries, in their X-ray spectra. Recently Reig & Roche (1999) suggested that there may exist a group of long period, persistent Be/X-ray binaries including X Per, RX J0146.9+5121, RX J0440.9+4431 and RX J1037.5−564 with similar characteristics.

The magnetic field strengths in X Per and RX J0146.9+5121 have not been measured since there are no cyclotron features directly observed in their X-ray spectra. However, relatively weak (a few 10^{11} G) magnetic field strengths in these two sources are indicated in several ways.

(1) It has been suggested that the cutoff energies in the power law spectra of X-ray pulsars are related to the pulsar magnetic field strengths (e.g., Makishima & Mihara 1992). If this relation can be applied to X Per and RX J0146.9+5121, then their magnetic field strengths B are around a few 10^{11} G, roughly one order of magnitude lower than those in typical binary X-ray pulsars.

(2) Quasi-periodic oscillations (QPOs) at a frequency of 54.1 mHz were detected in X Per with RXTE (Takeshima 1998). Assuming that the QPO frequency ν_Q represents the Keplerian frequency at the inner edge of the (temporary) accretion disk around X Per, or the difference between the Keplerian frequency and the stellar spin frequency, we obtain $B \lesssim 3 \times 10^{11} \dot{M}_{14}^{1/2} \nu_{Q,54}^{-7/6}$ G, for a $M = 1.4 M_\odot$ and $R = 10^6$ cm neutron star, where $\dot{M}_{14}$ is the mass accretion rate in units of $10^{14}\,\mathrm{g\,s^{-1}}$, and $\nu_{Q,54} = \nu_Q/54.1$mHz.

(3) A magnetic field $\sim 10^{11}$–10^{12} G has been estimated in RX J0146.9+5121, from the (average) spin-up rate ($-\dot{P} \simeq 5\ \mathrm{s\,yr^{-1}}$) and X-ray luminosity ($\sim (2-4) \times 10^{35}\,\mathrm{erg\,s^{-1}}$) observed between 1984 and 1993, with the assumption of the presence of a disk during this period (Hellier 1994).

Considering the above arguments, we adopt 10^{12} G as an upper limit of the magnetic field strengths in X Per and RX J0146.9+5121.

3. Origin of the long spin periods and magnetic field decay

A neutron star in binary systems with a high-mass companion star passes (at least) three evolutionary stages: (1) The "isolated radio pulsar" phase, in which the radiative pressure from the (rapidly rotating) neutron star is sufficient to keep the plasma of the companion's wind away, so that the evolution of the neutron star follows exactly that of isolated radio pulsars. (2) The "propeller" phase, in which the wind plasma interacts with the neutron star magnetosphere, but further accretion is inhibited by the centrifugal barrier, and the infalling matter is accelerated outward, taking away the angular momentum of the neutron star. At the end of this phase, the star is spun down to an equilibrium period (e.g., Wang & Robertson 1985)

$$P_{\rm eq} \simeq 50\, B_{12}^{6/7} \dot{M}_{14}^{-3/7}\ \mathrm{s}, \tag{1}$$

where $B_{12} = B/10^{12}$ G. (3) The wind accretion phase, in which the magnetospheric radius becomes smaller than the corotation radius, and accretion of the wind plasma is allowed.

The detailed evolution of the neutron star in a binary depends on the initial values of the spin period and the magnetic field, and the properties of the stellar wind from its companion. Although many Be/X-ray binaries show transient behavior, the persistent X-ray fluxes of X Per and RX J0146.9+5121 with little secular variation suggest the permanent presence of a high-density, low-velocity outflow from the Be companion stars to power the X-ray sources. Below we consider two kinds of stellar winds in which X Per and RX J0146.9+5121 were spun down.

Case a If the neutron stars have been spun down in the slow dense wind as present with a mass transfer rate $\sim 10^{14}\mathrm{g\,s^{-1}}$, magnetic field decay is inevitably required – from the current spin periods and Eq. (1), the initial magnetic fields must be $\gtrsim (2-5)\times 10^{13}$ G. The value of $P_{\rm eq}$ can never exceed ~ 100 s if the pulsars have had a constant magnetic field $\lesssim 10^{12}$ G.

Case b If, before the slow dense wind phase, the neutron stars had interacted with a fast ($V \sim 10^3\,\mathrm{km\,s^{-1}}$) polar wind for sufficiently long time, low mass transfer rates ($\lesssim$ a few $10^{10}-10^{11}\,\mathrm{g\,s^{-1}}$) may also account for the long spin periods with invariant magnetic fields $\sim 10^{12}$ G, *if* the total time $\tau_{\rm sd}$ taken in spin-down is less than the lifetime $\tau_{\rm ms}$ the companion star spends on the main sequence ($\lesssim 10^7$ yr, Lyubimkov et al. 1997). The magnitude of $\tau_{\rm sd}$ depends on the initial spin period P_0 and the spin period $P_{\rm a}$ when the radio pulsar phase ends. The latter is estimated to be $P_{\rm a} \simeq 1.6\dot{M}_{11}^{-1/4}B_{12}^{1/2}V_3^{-1/4}$s (Illarionov & Sunyaev 1975), or $P_{\rm a} \simeq 4.2\dot{M}_{11}^{-1/6}B_{12}^{1/3}V_3^{-5/6}$s (Davies & Pringle 1981), where $\dot{M}_{11} = \dot{M}/10^{11}\,\mathrm{g\,s^{-1}}$ and $V_3 = V/10^3\,\mathrm{km\,s^{-1}}$. Note that $P_{\rm a}$ is always $\gtrsim 1-10$ s when $B \lesssim 10^{12}$ G and $\dot{M} \lesssim 10^{11}\mathrm{g\,s^{-1}}$. If $P_0 \ll 1\text{ s} \lesssim P_{\rm a}$, as usually assumed for neutron stars, the spin-down time during the (first) radio pulsar phase depends only on $P_{\rm a}$ and is $\tau_{\rm sd}(\text{pulsar}) \gtrsim (2\times 10^7 - 2\times 10^9)$ yr. During the propeller phase, if the infalling material cooled efficiently, and was spun up to the local escape velocity at the magnetospheric radius, spin-down of the neutron stars would take a time (Wang & Robertson 1985)

$$\tau_{\rm sd}(\text{propeller}) \gtrsim 5\times 10^8 P_1^{-3/4}\dot{M}_{11}^{-3/4}B_{12}^{-1/2}\text{yr}, \tag{2}$$

where $P_1 = P/1$ s. So the total spin-down time $\tau_{\rm sd} = \tau_{\rm sd}(\text{pulsar}) + \tau_{\rm sd}(\text{propeller})$ is always much longer than the main sequence time $\tau_{\rm ms}$ of the companion stars. Even if the neutron stars were born slowly rotating ($P_0 \sim$ several seconds), and entered directly (or soon after birth) the propeller phase, equation (2) reveals that $\tau_{\rm sd} \simeq \tau_{\rm sd}(\text{propeller})$ is still longer than $\tau_{\rm ms}$ by roughly an order of magnitude. The neutron stars in these situations do not have enough time to reach the maximum period during the main-sequence evolution of the companion and to manifest themselves as X-ray pulsars until the companion star has evolved to become a supergiant.

We conclude that, unless they were born rotating very slowly (P_0 longer than tens of seconds) and had accreted from the fast polar wind for sufficiently long time, X Per and RX J0146.9+5121 must have initial magnetic fields much stronger than they have at present, to enable sufficient spin-down to their current periods; that is, the stellar magnetic fields must have decayed.

4. Discussion and conclusion

In the last section we have argued that field decay within 10^7 yr has occurred in the slowest known Be/X-ray pulsars X Per and RX J0146.9+5121. It remains to see whether the other two members of the persistent Be/X-ray pulsars, RX J0440.9+4431 and RX J1037.5−564, also have had their fields decayed. However, the common feature of a combination of the low-level, persistent X-ray luminosities and long spin periods indicates that the pulsars in these systems all currently have relatively weak magnetic fields, which may be related to field decay. We note that Livio, Xu & Frank (1998) recently reached a similar conclusion (but in a different way) that strong magnetic fields ($> 10^{12}$ G) are required to decay rapidly (with an exponential timescale $\sim 10^7$ yr) to interpret the discrepancy between the theoretically expected number of detectable isolated old neutron stars ($10^2 - 10^3$) and the actually detected number of candidates $(2-3)$. Since X Per and RX J0146.9+5121 have accreted mass of at most $\sim 10^{-5}\,M_{\odot}$. This implies that tiny mass accretion can result in significant field decay (by a factor of $\gtrsim 10$) in strong field neutron stars.

Acknowledgments. This work was supported by National Natural Science Foundation of China.

References

Bhattacharya, D., van den Heuvel, E.P.J. 1991, Phys. Rep. 203, 1

Davies, R.E., Pringle, J.E. 1981, MNRAS 196, 209

Haberl, F., Angelini, L., Motch, C., White, N.E. 1998, A&A 330, 189

Hellier, C. 1994, MNRAS 271, L21

Illarionov, A.F., Sunyaev, R.A. 1975, A&A 39, 185

Livio, M., Xu, C., Frank, J. 1998, ApJ 492, 298

Lyubimkov, L.S., Rostpchin, S.I., Roche, P., Tarasov, A.S. 1997, MNRAS 286, 549

Makishima, K., Mihara, T. 1992, in Frontiers in X-ray Astronomy, ed. Y. Tanaka & K. Koyama (Tokyo: Uni. Acad. Press), 23

Nagase, F. 1989, PASJ 41, 1

Reig, P., Roche, P. 1999, MNRAS 306, 100

Takeshima, T. 1998, in IAU Symp. 188, The Hot Universe, ed. K. Koyama, S. Kitamoto & M. Itoh (Kluwer Academic Publishers), 368

Wang, Y.-M., Robertson, J.A. 1985, A&A 151, 361

Wijers, R. 1997, MNRAS 287, 607