Growth of magnetic fields in accreting millisecond pulsars

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ABSTRACT

R-modes can generate strong magnetic fields in the core of accreting millisecond neutron stars (NSs). The diffusion of these fields outside the core causes the growth of the external magnetic field and thus it affects the evolution of the spin down rates $P$ of the millisecond pulsars (MSPs). The diffusion of the internal magnetic field provides a new evolutionary path for the MSPs. This scenario could explain the large $P$ of the pulsars J1823-3021A and J1824-2452A.

Key words: millisecond pulsars – magnetic fields – r-modes.

1 INTRODUCTION

In recent papers it has been proposed a mechanism based on the r-mode instability for the evolution of the internal magnetic field in millisecond accreting compact stars (Cuofano & Drago 2010, Bonanno et al. 2011, Cuofano et al. 2012). R-modes represent a class of oscillation modes in rotating neutron stars, which are unstable with respect to the emission of gravitational waves (Andersson & Kokkotas 2001). Only the existence of efficient damping mechanisms can suppress this instability and allows neutron stars to rotate at high frequencies. An important mechanism for damping is dissipation which can be provided by shear and bulk viscosities converting the rotational energy of the star into heat. Another very efficient source of damping is dissipation which can be provided by shear and bulk viscosities converting the rotational energy of the star into heat. Another very efficient source of damping is dissipation which can be provided by shear and bulk viscosities converting the rotational energy of the star into heat. Another very efficient source of damping is dissipation which can be provided by shear and bulk viscosities converting the rotational energy of the star into heat.

Here we analyze the evolution of the external magnetic field during/after accretion due to the diffusion outside the core of the magnetic field generated by r-modes. The increase of the external magnetic field implies a growth of the spin down rate $P$ of the millisecond NSs. Finally we show that this mechanism can account for the large $P$ observed for the two pulsars J1823-3021A and J1824-2452A.

2 EVOLUTION OF THE EXTERNAL MAGNETIC FIELD

The toroidal magnetic fields generated in the core of accreting millisecond neutron stars are in the range $B_{\text{tor}}^{\text{pol}} \sim [10^{12} - 10^{14}]$ G (Cuofano & Drago 2010, Cuofano et al. 2012). These strong toroidal fields can be stabilized with respect to the Tayler instability by a much smaller poloidal component (Braithwaite 2009) that we assume in the range $B_{\text{pol}}^{\text{pol}} \sim [10^{10} - 10^{11}]$ G. We indicate with $t_0$ the moment at which the new internal poloidal component is fully developed.

In order for the poloidal field to affect the spin frequency evolution of the star it is necessary that the it diffuses outside of the core. A crucial issue concerns the time-scale $\tau_{\text{diss}}$ on which the internal poloidal component can diffuse. Unfortunately there are no precise estimates about the value of $\tau_{\text{diss}}$ in the presence of a layer of superconducting material in the inner crust. A detailed description of the diffusion of the internal magnetic field is beyond the scope of this paper. We limit ourselves to note that if $\tau_{\text{diss}}$ is shorter than a few ten million years the star enters a propeller regime too quickly and it is impossible to accelerate the NS to the higher observed spin frequencies. On the other hand if $\tau_{\text{diss}}$ is much larger than $10^{10}$ yr the expulsion of the magnetic field would be phenomenologically irrelevant. It is thus necessary that the diffusion of the internal poloidal field

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takes place on a time-scale $\tau_{\text{disk}} \approx [10^8 - 10^{10}]$ yr. These estimates are compatible with the theoretical predictions given by [Gepert et al. (1999)] and [Koenck & Gerpert (2000)].

We begin our analysis at $t = t_0$. We follow the evolution of the external magnetic field $B^{\text{ext}}$ while the internal field $B^{\text{int}}$ diffuses outside of the core. For simplicity we assume an exponential growth of the external magnetic field:

$$B^{\text{ext}}(t) = B^{\text{ext}}(t_0) + B^{\text{int}}(1 - \exp(-\Delta t / \tau_{\text{disk}}))$$

where $\Delta t = t - t_0$ and the initial external magnetic field is assumed to be $B^{\text{ext}}(t_0) \sim 10^8$ G. The latter is a rather typical strength for neutron stars in Low Mass X-ray Binaries (LMXBs).

In Figure 1 we show the evolution of the external magnetic field obtained by using Eq. (1).

In the following we consider the diffusion of the new generated internal magnetic field separately in the case in which mass accretion is still active and in the case it has terminated.

### 2.1 Evolutionary scenario without mass accretion

Here we consider the evolution of a recycled neutron star in a scenario in which the mass accretion phase ends within a few million years after $t_0$. In this case the evolution of the spin period of the star is quite simple because it is not necessary to take into account the interaction between the accretion disk and the magnetic field during the diffusion of $B^{\text{int}}$. The total angular momentum of the star satisfies the equation (Becker 2009):

$$\frac{dJ}{dt} = -\frac{16}{3} \left(\frac{\sigma}{c}\right)^3 \frac{R^6 (B^{\text{pol}}(t))^2}{P^2}$$  

where $c$ is the speed of light, $J \equiv \hbar \Omega$ is the angular momentum of the star and $B^{\text{pol}}_{\text{ext}}$ is obtained from Eq. (1).

In the following we indicate with $P_0$ the spin period at the time $t = t_0$ and we treat $P_0$ as a free parameter. Notice that the internal magnetic field can develop only if the star enters the r-mode instability region (Cuofano & Drago 2010). The upper limit of this region is characterized by a period $P_{\text{high}}$, whose precise value depends on the viscous properties of the star and on the possible existence of the Ekman layer (Bondarescu et al. 2007). Therefore also the parameter $P_0$ is bound by the condition $P_0 \leq P_{\text{high}} \leq 5$ ms.

We stress that $B^{\text{pol}}_{\text{int}}$ and $P_0$ are not the same for every star. They actually depend on the very complicated evolution of the internal magnetic field which in turn is related to the values of $M$ and $B^{\text{pol}}_{\text{ext}}(t_0)$ (see for instance Figure 3 of Cuofano & Drago (2010)).

Results for the evolutionary paths in the $P-\dot{P}$ plane are shown in Figure 2. The shaded strip includes the possible trajectories of the stars (the red arrows are included as guidelines for the temporal evolution). The shape of this strip is regulated mainly by the three parameters $\tau_{\text{disk}}, B^{\text{pol}}_{\text{int}}$ and $P_{\text{high}}$ ($B^{\text{pol}}_{\text{ext}}(t_0)$ plays a marginal role). The width of the strip at the beginning is fixed by $P_{\text{high}}$ and $P_{\text{low}}$. The latter parameter corresponds to the minimal period reachable by a recycled MSP. Observationally its value is of the order of $P_{\text{low}} \approx 1.3$ ms (Chakrabarty et al. 2003; Chakrabarty 2004). $B^{\text{pol}}_{\text{int}}$ fixes the width of the strip at late times and $\tau_{\text{disk}}$ regulates the height of the elbow: the smaller $\tau_{\text{disk}}$, the higher the elbow.

1 This value can be justified theoretically by considering the deformation of the star generated by the internal toroidal field (Cuofano et al. 2012).
Growth of magnetic fields in accreting MSPs

3 MILLISECOND PULSARS J1823-3021A AND J1824-2452A

In the previous Section we have presented a general scenario for the evolution of MSPs when the production and the diffusion of the internal magnetic field is taken into account. In this Section we concentrate on the cases of the two isolated pulsars J1823-3021A and J1824-2452A.

In the most widely discussed model, MSPs have been re-accelerated through mass accretion, in particular by having spent a fraction of their lives as part of a LMXB. The way by which they end up as isolated pulsars is still not fully understood. A possibility is that the companions are destroyed through ablation caused by energetic radiation from the pulsar (Bhattacharya & van den Heuvel 1991). Another possibility requires mass loss from the companion which can take place in very close binary systems due to tidal dissipation (Radhakrishnan & Shukri 1986). A totally different scheme to produce an isolated MSP is the one in which the pulsar had an interaction with another star or binary in the globular cluster, and was spun-up in the process (Lyne et al. 1996). In the following we will concentrate on the scenario in which MSPs are produced in LMXBs.

The pulsar J1823-3021A, located in the globular cluster NGC 6624, was discovered in 1994 (Biggs et al. 1994, 1996). The Fermi Large Area Telescope has recently detected the γ ray counterpart of its pulsations (Fermi Lat 2011) with a luminosity of $L_\gamma = 8.4 \pm 1.6 \times 10^{34}$ ergs s$^{-1}$, the highest observed γ ray luminosity for any MSP. The pulsation period $P = 5.44$ ms and the observed spinning down rate is extremely large $\dot{P}_{\text{obs}} = +3.38 \times 10^{-18}$ s$^{-1}$, larger by far than the typical value for other MSPs. These properties make J1823-3021A an extremely interesting stellar object. The total observed γ ray emission implies that a significant fraction of $\dot{P}_{\text{obs}}$ is due to the intrinsic spinning down rate $\dot{P}$ (Fermi Lat 2011). Within the standard magnetic dipole model for pulsar emission, such a large $\dot{P}$ is generated by a large surface magnetic field $B_0$, larger than $10^{10}$ G. This fact represents a puzzle for standard MSP theory (Fermi Lat 2011): if J1823-3021A was spun-up by mass accretion, in particular by the fusion of the internal magnetic field is taken into account. In

Remarkably, we can populate the region above the line corresponding to the Eddington limit (dashed line). This is exactly the region where J1823-3021A and J1824-2452A lie.

2.2 Evolutionary scenario with mass accretion

If the mass accretion phase lasts tens or hundreds of million years after $t_0$, the evolutionary scenario is more complicated.

The plasma flowing onto the neutron star forms an accretion disk whose inner edge is given by the coupling radius of the magnetosphere (of the same order of magnitude of the Alfvén radius) $r_{\text{mag}} \sim B^{1/7} R^{2/7} (M \sqrt{\gamma GM})^{-2/7}$ (Taurs 2012). The interaction between the magnetic field of the compact object and the conducting material flowing from its companion can provide the necessary torque $\dot{J}_m = M (G M r_{\text{mag}})^{1/2}$ to spin up the pulsar (Shapiro et al. 1983). However, under certain conditions, it is possible that this interaction leads to a torque reversal. The growth of the external field $B_{\text{ext}}$ causes the magnetic boundary $r_{\text{mag}}$ to move outward relative to the corotation radius $r_{\text{co}} = (GM/\Omega_c)^{2/3}$ defined as the distance at which the spin frequency of the star is equal to the Keplerian frequency. The star enters a propeller phase when $r_{\text{mag}} > r_{\text{co}}$: a centrifugal barrier prevents the material to flow onto the star and a new braking torque $\dot{J}_M = -GM (G M r_{\text{mag}})^{1/2}$ acts to slow down the pulsar (Taurs 2012).

In Figure 3a we show a typical evolutionary path for an accreting neutron star if the diffusion of the internal poloidal component $B_{\text{in}}$ is taken into account. The growth of the external magnetic field $B_{\text{ext}}$ leads to the end of the spin-up phase. The star evolves into an equilibrium spin phase, it alternates between spin-up and spin-down ($r_{\text{mag}} \sim r_{\text{co}}$) and finally it appears as a radio pulsar at the end of the mass accretion phase.

Finally, from the analysis presented above we can notice that in order to reach high spin frequencies it is necessary a mass accretion rate $\dot{M} > 10^{-9} M_\odot$ yr$^{-1}$ (see Figure 3b).
strong X-ray pulses \cite{Rots1998} and a large second period derivative $\dot{P}$ \cite{Cognard1996}. As for J1823-3021A, the large $\dot{P}$ implies a surface magnetic field $B_0 > 10^9$ G and the combination of values $(P-\dot{P})$ is difficult to explain in the standard MSPs theory.

Note that these anomalous pulsars can be explained in the standard model if the accretion occurred at super-Eddington rate. About such a possibility, we note that all the accreting compact stars detected up to now in LMXBs have steady mass accretion rates $\dot{M} \ll M_{\text{Edd}}$ \cite{Galloway2008}. Moreover, taking into account also the interaction between the external magnetic field and the accretion disk, a minimal value for the mass accretion rate $\dot{M} \geq 5 \times 10^{-8} M_{\odot} \text{yr}^{-1}$ is necessary to accelerate the stars up to the present spin frequency. For lower values of $\dot{M}$ the accreting NS enters a propeller regime that prevents a further acceleration.

In our analysis we have presented a scheme in which the MSPs can populate the region occupied by J1823-3021A and J1824-2452A. It is important to remark that the existence of a propeller phase does not invalidate the possibility to interpret these two special MSPs in our scheme. Indeed, in Figure 3, we show that the spin frequency of the star does not change significantly during the spin equilibrium phase: even if a fast spin-down of the star takes place during the propeller regime \cite{Cuofano2012}, the star nevertheless will continue to appear as a radio pulsar in the shaded area of Figure 2. Concerning the two anomalous stellar objects they are no more accreting and if a propeller phase took place during accretion it is clearly already over. The exact position in the $P-\dot{P}$ plane before a possible propeller phase cannot be determined precisely, but it was located at higher frequencies: the existence of this phase would make therefore even more difficult to interpret these two objects within the standard pulsar model (because they would lie further from the Eddington limit) but it is easy to accommodate in our model.

4 CONCLUSIONS

We have discussed the evolution of the external magnetic field of recycled MSPs due to the diffusion of strong internal magnetic fields generated by r-modes during the mass accretion phase. Our analysis is based on the previous work of \cite{Cuofano2010} and \cite{Bonanno2011} where it has been shown that r-modes generate strong internal magnetic fields in accreting compact stars. We have shown that the growth of the external magnetic field affects the evolution of the spin-down rate $\dot{P}$ of the MSPs and that this mechanism can explain the high $\dot{P}$ of J1823-3021A and of J1824-2452A. Our analysis open new evolutionary paths for the recycled MSPs in the $P-\dot{P}$ plane.

\footnote{LMXBs are often transient sources and may have short-term active periods of intense accretion; large $\dot{M}$ presented in \cite{Galloway2008} in parentheses refer to these active periods and not to steady accretion.}

ACKNOWLEDGEMENTS

G.P. acknowledges financial support from the Italian Ministry of Research through the program Rita Levi Montalcini.

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