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Fallback accretion onto magnetized neutron stars and the hidden magnetic field model

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Abstract. The observation of several neutron stars with relatively low values of the surface magnetic field found in supernova remnants has led in recent years to controversial interpretations. A possible explanation is the slow rotation of the proto-neutron star at birth which is unable to amplify its magnetic field to typical pulsar levels. An alternative possibility, the hidden magnetic field scenario, seems to be favoured over the previous one due to the observation of three low magnetic field magnetars. This scenario considers the accretion of the fallback of the supernova debris onto the neutron star as the responsible for the observed low magnetic field. In this work, we have studied under which conditions the magnetic field of a neutron star can be buried into the crust due to an accreting fluid. We have considered a simplified toy model in general relativity to estimate the balance between the incoming accretion flow an the magnetosphere. We conclude that the burial is possible for values of the surface magnetic field below 10^{13} G. The preliminary results reported in this paper for simplified polytropic models should be confirmed using a more realistic thermodynamical setup.

1. Introduction

The hidden magnetic field scenario proposed by Shabaltas & Lay [1] offers a viable explanation for the unusual features observed in Central Compact Objects (CCOs). CCOs are isolated young neutron stars with no radio emission and located near the center of young supernova remnants (SNR). Nowadays, three such neutron stars (PSR E1207.4-5209, PSR J0821.0-4300, PSR J1852.3-0040) show an inferred magnetic field significantly lower than the common values for neutron stars. PSR E1207.4-5209 in the supernova remnant PKS 1209-51/52 was the first discovered CCO [2, 3] and has been extensively studied. Its period $P = 424.130751(4)$ ms and period derivative $\dot{P} = (9.6 \pm 9.4) \times 10^{-17}$s s^{-1} imply a surface magnetic field strength $B_s < 3.5 \times 10^{11}$ G, and a characteristic age of $\tau_c \equiv P/2\dot{P} > 24$ Myr. PSR J0821.0-4300 in Puppis A [4] is a 112 ms pulsar with $\dot{P} < 8.3 \times 10^{-15}$s s^{-1}. This value of $\dot{P}$ implies a surface magnetic dipole field strength $B_s < 9.8 \times 10^{11}$ G. The characteristic age of PSR J082-4300 is $\tau_c > 220$ kyr. Finally, PSR J1852-0040 in Kes 79 [5] has a period of $P = 105$ ms, a period derivative of $\dot{P} < 7 \times 10^{-14}$s s^{-1}and a surface magnetic field strength of $B_s < 3 \times 10^{12}$ G, and its spin-down age is $\tau > 24$ kyr. In all cases, the difference between the characteristic age of the neutron star and the age of their the remnant indicates that the neutron stars were born spinning at their present periods.

Similar to these observations of CCOs, there also exist three additional observations of so-called low magnetic field magnetars [6], SGR 0418+5729, Swift J1822-1606 and 3XMM J185246.6+003317. SGR 0418+5729 [7] has a period of $P = 9.07838822$ s and a period derivative $\dot{P} = 4 \times 10^{-15}$s s^{-1}, which leads to a surface dipolar magnetic field of $B_s = 6 \times 10^{12}$ G. This measurement confirms SGR 0418+5729 as the lowest magnetic field magnetar known. The inferred spindown age is ~ 550 kyr. Swift J1822-1606 [8] has a period of $P = 8.43772016$ s, a period derivative $\dot{P} = 2.14 \times 10^{-14}$s s^{-1},a surface magnetic field of $B_s = 1.4 \times 10^{13}$ G and spindown age of 6300 kyr. Finally, 3XMM J185246.6+003317 [9] has a period of $P = 11.55871346$ s, a period derivative $\dot{P} < 1.4 \times 10^{-13}$s s^{-1}, which, assuming the classical magneto-dipolar braking model, gives a limit on the dipolar magnetic field of $B_s < 4.1 \times 10^{13}$ G. The spindown age is > 1300 kyr. The spectral characteristics and activity of these objects confirm their identification as magnetars but, as in the case of the CCOs presented before, they have values of the magnetic field significantly lower than the typical values for their class (i.e. $10^{14} - 10^{15}$ G).

The first explanation for the unusual magnetic field found in these objects assumes that the neutron stars were born with a low value of the magnetic field. This idea is based on field amplification models where the magnetic field is amplified by the turbulent dynamos of the proto-neutron star [10, 11]. Therefore, the low values of the magnetic field are due to the fact that the slow rotation at birth of the neutron star does not sufficiently amplify the magnetic field. However, recent studies have shown that even in the absence of rapid rotation magnetic fields in proto-neutron stars can be amplified by other mechanisms such as convection and the standing accretion shock instability (SASI) [12, 13].

The other possible explanation is the hidden magnetic field model. After the supernova explosion, when the neutron star is born, the supernova shock is still traveling outwards through the external layers of the star. When this shock crosses a discontinuity in density, part of it can be reflected and move backwards towards the neutron star. The total mass accreted by the reverse shock in this process is $\sim 10^{-4} - 10^{-1} M_\odot$ in a typical timescale of hours to days [14]. Such high accretion rate can compress the magnetic field of the neutron star which can eventually be buried into the neutron star crust. As a result, the value of the external magnetic field would be significantly lower than the internal 'hidden' magnetic field. When accretion stops, the magnetic field may reemerge after a certain period of time.

There exist several works that have studied the viability of this scenario. On the one hand, the initial works studied the process of reemergence [15, 16, 17] using simplified 1D models and dipolar fields. These works established that the timescale for the magnetic field reemergence is about $1 - 10^7$ kyr, depending on the depth at which the magnetic field is buried. More recent works have confirmed this result. Ho [18] observed similar timescales for the reemergence using a 1D cooling code. Bernal, Lee and Page [19] performed 1D and 2D simulations of a single column of material falling onto a magnetized neutron star and showed how the magnetic field can be buried into the neutron star crust. Viganò and Pons [20] carried out simulations of the evolution of the interior magnetic field during the accretion and magnetic field submergence phase. Our goal is to perform 2D MHD simulations of the accretion phase. In this work we present preliminary results of initial tests aimed at devising the strategy we must follow to perform such simulations and at identifying the potential difficulties. Complete result will be presented elsewhere [21].

2. Pressure balance in an accreting magnetosphere

In this work, we follow the notation defined in [22]. The neutron star magnetosphere refers to the area surrounding the star where the magnetic pressure dominates over the thermal pressure of the accreting fluid. We call magnetopause to the interface between the magnetically dominated area and the thermally dominated area. The space of parameters of the problem includes the

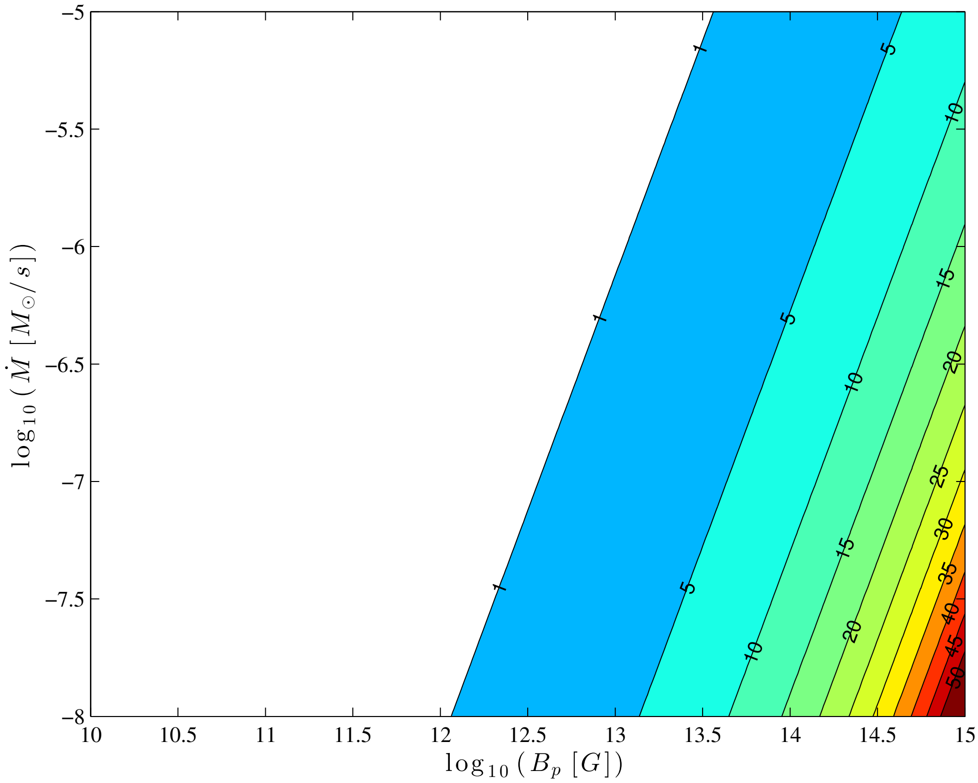

Figure 1. Radial position of the magnetopause for several values of the accretion rate $\dot{M}$ and magnetic field at the pole B_p. The lines indicate isocontours of $r_{\rm mp}/r_{\rm star}$ referred to the radius of the neutron star. Values under 1 are shown in white.

surface magnetic field at the pole of the neutron star, typically in the range $B_p \in [10^{10} - 10^{15}]$ G, and the accretion rate of the infalling material, in the interval $\dot{m} \in [10^{-8} - 10^{-5}] M_\odot/s$. The latter values are derived from the total mass accreted by the reverse shock in a time scale of a few hours.

For our first test we model the accretion fluid with the so-called Michel solution describing the spherical accretion of an unmagnetized relativistic fluid [23]. The magnetosphere is generated by a simple dipole magnetic field and a polytropic equation of state is used to describe the fluid. Our aim is to compute the position of the magnetopause at which the balance between the accreting fluid and the magnetosphere is reached. For this purpose we search for a pressure balance at the equator for the span of parameters. As the velocity of the fluid plays an important role in the form of ram pressure, we include in the expression of the pressure balance an extra term that models the effect of the velocity, namely

$$\frac{B^2}{2} = P_{\rm fluid} + \rho h W^2 v^2, \tag{1}$$

where $\frac{B^2}{2}$ and $P_{\rm fluid}$ are the pressures generated by the magnetic field and the fluid respectively, ρ is the density of the fluid, h is the specific enthalpy, W is the Lorentz factor and v is the velocity. The restriction given by this equation must be satisfied at the magnetopause.

Fig. 1 shows the position of the equilibrium magnetopause ($r_{\rm mp}$) for the span of parameters we are considering. Values of $r_{\rm mp}/r_{\rm star} < 1$ indicate that the pressure equilibrium position is reached inside the star, and therefore the magnetic field can be buried totally. This is the case

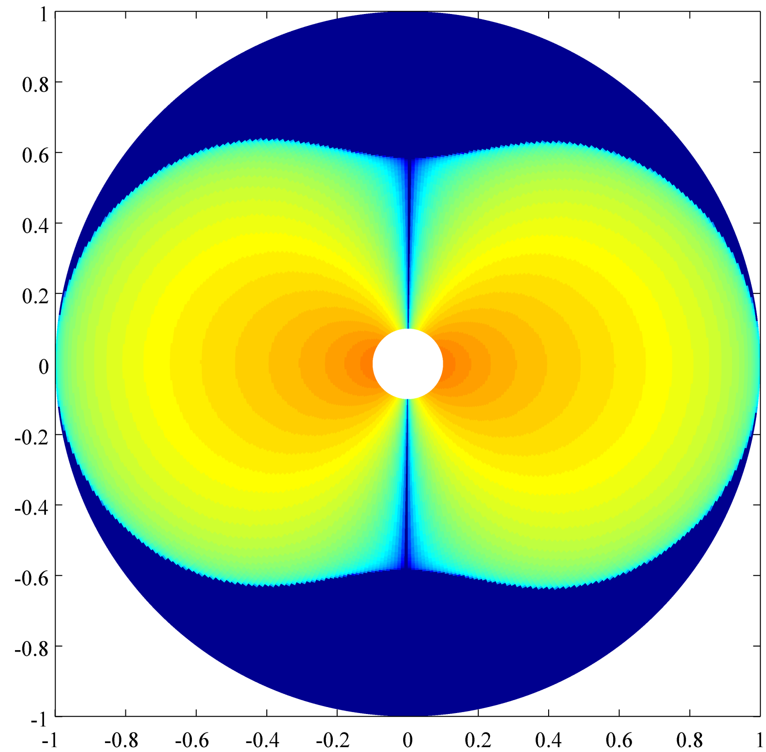

Figure 2. Magnetosphere generated by the multipolar expansion of a dipole proposed by Michel [22]. The white circle at center represents the neutron star, where the magnetic field is not calculated. The scale is normalized to be 1 at the magnetopause.

for magnetic field values below 10^{12} G for all accretion rates considered. In the case of magnetars with $B_p \in [10^{14} - 10^{15}]$ G, only the highest accretion rates considered can compress the magnetic field near the neutron star surface, but not close enough to bury it at the equator. However, it could still be possible to have the magnetic field partially buried in higher latitudes of the star.

3. Equilibrium magnetosphere

In the second test we compute the magnetosphere structure following the procedure proposed in [22]. The dipolar magnetic field is confined by gravitationally trapped plasma external to the star. The magnetic field is modeled as a dipole plus an arbitrary set of multipoles. The vector potential is

$$A_\phi = \sin\theta[r^{-2} - \sum_{n=1}^{\infty} a_n r^n P_n'(\cos\theta)], \quad (2)$$

where P_n' is the derivative with respect to $\cos\theta$ of the nth Legendre polynomial. The field lines are given by lines of constant $f = r\sin\theta A_\phi$ and they are tangent to the surface given by the magnetopause. The goal of this test is to have an idea of the shape of a magnetosphere confined by the accreting fluid before performing the actual numerical simulations.

The shape of Michel's confined magnetosphere is shown in Fig. 2. The radius and the magnetic field values have been normalized for generality. We can see how the magnetosphere approaches zero at the poles as expected for a dipolar magnetic field. This result gives us information of the changes in the geometry of the magnetic field resulting from the accretion we can expect. In a more realistic simulation the initial magnetic field has to be confined by the accretion fluid.

4. Conclusions

The initial results presented here provide support to the idea that the hidden magnetic field scenario is plausible for values of the magnetic field $B_p \in [10^{10} - 10^{13}]$ G, typical in isolated neutron stars, and for the typical accretion rates produced by the supernova reverse shock. In the case of magnetars, the scenario seems to be less plausible as the equatorial point of pressure balance is located far from the neutron star, implying that it could be difficult to bury the magnetic field. We note however that the models we have used in this preliminary work are fairly simple and the results may change accordingly when considering a more realistic scenario. From a technical point of view, the feasibility to carry out the actual simulations is going to be conditioned by the ratio between the magnetic and the thermal pressure. An ideal MHD numerical code must separate the thermal and magnetic contributions to the energy, which, in the scenario under study, is going to be a numerically challenging goal.

The second test reported in this work is key to understand the shape of a confined magnetic field. In future simulations we must compute a force-free solution for the magnetic field that takes into account the boundary conditions imposed by the accreting fluid. In the same way, we must impose very low densities in order to assure a force-free solution in the whole magnetosphere. However, the multipolar expansion of the dipole given by Eq. (2) is not general due to its dependence on the number of multipoles N used to compute the solution, which in our case was not too large as our algorithm shows stability and convergence problems for large values of N. In addition, this expression does not allow to impose arbitrary boundary conditions in order to study different field configurations.

In a future work [21] we plan to use a more realistic equation of state that will allow us to control the temperature and the composition of the accreting fluid. Furthermore, the magnetic field must be computed with increased generality to accommodate different magnetic field configurations and impose distinct magnetopause positions. The incorporation of these new ingredients in a time-dependent MHD numerical code is ongoing and results for a larger number of astrophysical scenarios will be presented elsewhere [21].

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