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Accretion-induced Distortion of the Polar Cap Magnetic Field of an Accreting Neutron Star

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Abstract. We compute the distorted magnetic field structure of a neutron star accreting at its poles as a function of accreted mass M_{a} by evolving an initial dipole through a quasistatic sequence of Grad-Shafranov equilibria. Our calculation is the first to (i) follow the development of high-order multipoles due to equatorial hydromagnetic spreading, and (ii) maintain strict flux freezing between the initial and final states. We find that one requires $M_{\mathrm{a}} \geq 10^{-5} M_{\odot}$ to significantly distort the field, higher than previous estimates ($\sim 10^{-10} M_{\odot}$), and that buoyant magnetic bubbles can form when the distortion is severe.

1. Introduction

Low-field neutron stars in binary systems are observed to have a magnetic dipole moment μ which decreases monotonically with accreted mass M_{a} (Taam & van den Heuvel 1986; van den Heuvel & Bitzaraki 1995). Several mechanisms have been proposed to explain the magnetic field reduction: (i) accelerated Ohmic decay (Urpin & Geppert 1995), (ii) interactions between vortices and fluxoids in the superfluid, superconducting stellar interior (Muslimov & Tsygan 1985), and (iii) magnetic screening or burial (Arons & Lea 1980). For a brief review, see Melatos & Phinney (2001).

Here we focus on magnetic field burial, where the currents generating the original dipole field are partially neutralised by accretion-induced surface currents. We solve numerically for the equilibrium hydromagnetic configuration of the star, as a function of accreted mass M_{a}. A novel aspect of this calculation is the enforcement of flux freezing in passing from the initial to the final state. Moreover, previous calculations (Brown & Bildsten 1998; Hameury et al. 1983) were restricted to the polar accretion column, ignoring equatorward magnetic stresses, whereas we solve for the magnetic field at all latitudes.

2. Hydromagnetic Equilibria

The steady-state ideal-MHD equations for an isothermal atmosphere ($p = c_s^2\rho$) reduce to the force equation

$$\nabla p + \rho\nabla\phi - \mu_0{}^{-1}(\nabla \times \mathbf{B}) \times \mathbf{B} = 0, \quad (1)$$

where **B** denotes magnetic field, ρ mass density, p pressure, and ϕ gravitational potential. For an axisymmetric configuration we may write $\mathbf{B} = \nabla\psi(r,\theta)/(r\sin\theta) \times \hat{\mathbf{e}}_\phi$, leading to the Grad-Shafranov equation (Payne & Melatos 2002)

$$\Delta^2\psi = F'(\psi)\exp[-(\phi-\phi_0)/c_s^2]. \tag{2}$$

$F(\psi) = p(\psi)\exp[(\phi-\phi_0)/c_s^2]$ traces the pressure at the stellar surface from pole to equator, ϕ_0 is the surface gravitational potential, and Δ^2 is the Grad-Shafranov operator (Payne & Melatos 2002). We assume, and verify a posteriori, that the hydromagnetic length-scale $|\mathbf{B}|/|\nabla\mathbf{B}|$ is much smaller than the hydrostatic length-scale $|p|/|\rho\nabla\phi|$, so that $\phi = GM_* r/R_*^2$. To close the problem, and connect the initial and final states uniquely, we require mass to be conserved in flux tubes:

$$\frac{dM}{d\psi} = 2\pi\int_C \rho(r,\theta)\frac{r\sin\theta}{|\nabla\psi|}ds. \tag{3}$$

C is a magnetic field line, and the mass-flux distribution $dM/d\psi$ is prescribed.

With $\psi = 0$ at the pole and $\psi = \psi_*$ at the equator, the total accreted mass M_a is assumed to be distributed by $dM/d\psi = (M_a/2\psi_a)\exp(-\psi/\psi a)$, where $\psi_a = \psi_* R_*/R_a$ is the flux enclosed by the inner edge of the accretion disk at a distance R_a. For the boundary conditions, we fix ψ to be dipolar at $r = R_*$, assume north-south symmetry, fix the $\psi = 0$ field line and leave the field free at large r.

Equations (2) and (3) are solved numerically using an iterative scheme (Mouschovias 1974), overrelaxing (2) at each step and then underrelaxing (2) and (3). Convergence to the final state occurs monotonically for $M_a \lesssim 10^{-5}M_\odot$ but is more erratic for larger M_a. We also solve (2) and (3) analytically by an appropriate Green function method as verification.

3. Magnetic Burial

Accreted matter accumulates in a polar column until the hydrostatic pressure gradient at the base of the column exceeds the magnetic tension, dragging the magnetic field along the stellar surface toward the equator (Melatos & Phinney 2001). Given an initial magnetic field and a mass-flux distribution $dM/d\psi$, mass slides along flux tubes until ∇p balances $\rho\nabla\phi$ along **B**. The Lorentz force balances ∇p and $\rho\nabla\phi$ perpendicular to **B**. The resulting current density ${\mu_0}^{-1}(\nabla\times\mathbf{B})$ screens the original magnetic field.

Figure 1 shows an example of an equilibrium for $M_a = 10^{-5}M_\odot$. Note the presence of magnetic field lines disconnected from the surface of the neutron star, which we refer to as *magnetic bubbles*. These are neither artifacts of the numerical procedure nor legacies of the polar boundary condition; by solving (2) analytically for a prescribed source term one can show that contours with $\psi > \psi_a$ and/or $\psi < 0$ are created above a critical $M_a \sim 10^{-5}M_\odot$ by the screening currents (Payne & Melatos 2002). The critical M_a depends on the form of $dM/d\psi$.

Figure 2 shows the dipole moment as a function of $(r - R_*)$ for different values of M_a. Note that the solution converges poorly for $M_a \gg 10^{-5}M_\odot$. The important result here is that μ is not reduced significantly until $\sim 10^{-5}M_\odot$

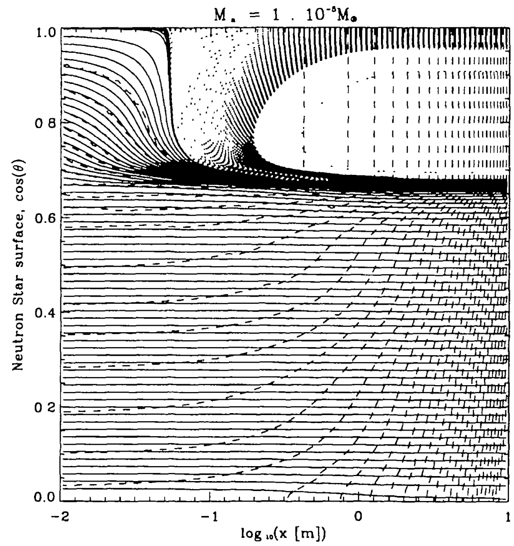

Figure 1. Magnetic field lines (solid), density contours (dashed) and magnetic field lines disconnected from the star surface (dotted), for $M_{\rm a} = 10^{-5} M_\odot, B_* = 10^8 {\rm T}, r_0 = c_s^2 R_*/(GM_*) = 0.54{\rm m}$, $R_{\rm a}/R_* = 10$

has been accreted. This agrees roughly with observational evidence from high mass x-ray binaries and radio binary pulsars (Taam & van den Heuvel 1986) and is larger than previous estimates ($M_{\rm a} \sim 10^{-10} M_\odot$; Brown & Bildsten 1998; Hameury et al. 1983) which did not take the equatorward magnetic stresses into account.

While the formation and dynamics of the bubbles have not been explored fully, we speculate that they are unlikely to represent a stable equilibrium state. For example, they may rise buoyantly, expelling some of the accreted mass. We cannot study such evolution in a steady-state problem. In addition, we see evidence of Parker instabilities in our numerical calculations, such as $F(\psi)$ oscillating with ψ because the polar magnetic field develops a component perpendicular to the gravitational field. The code accurately converges to the final nonlinear state (Mouschovias 1974). We do not believe that Parker instabilities cause the magnetic bubbles (Payne & Melatos 2002).

4. Conclusion

There are two main results of this work: (i) $M_{\rm a} \gtrsim 10^{-5} M_\odot$ is required to significantly reduce μ, $\sim 10^5$ times higher than previously calculated. (ii) Magnetic bubbles appear for $M_{\rm a} \gtrsim 10^{-5} M_\odot$, which may be buoyantly unstable.

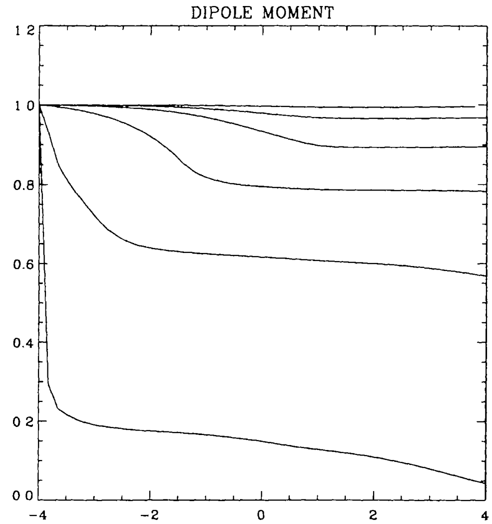

Figure 2. Plot of the dipole moment $\mu(x)$ as a function of distance $\log_e(x/r_0)$ from the neutron star surface $x = (r - R_*)$, normalised to $\mu(R_*)$ for $M_a/M_\odot = 10^{-6}$(top), $3 \times 10^{-6}, 10^{-5}, 3 \times 10^{-5}, 10^{-4}, 3 \times 10^{-4}$ (bottom).

References

Arons, J., & Lea, S. M., 1980, ApJ, 235, 1016

Brown, E. F., & Bildsten, L., 1998, ApJ, 496, 915

Cumming, A., Zweibel, E., & Bildsten, L., 2001, ApJ, 557, 958

Hameury, J. M., Bonazzola, S., Heyvaerts, J., & Lasota, J. P., 1983, A&A, 128, 369

Litwin, C., Brown, E. F., & Rosner, R., 2001, ApJ, 553, 788

Melatos, A., & Phinney, E. S., 2000, Publ. Astron. Soc. Australia, 18, 421

Mouschovias, T. C., 1974, ApJ, 192, 37

Payne, D. J. B. & Melatos, A., 2002, in preparation

Taam, R. E., & van den Heuvel, E. P. J., 1986, ApJ, 305, 235

van den Heuvel, E. P. J., & Bitzaraki, O., 1995,A&A, 297, L41

Urpin, V., & Geppert, U., 1995, MNRAS, 275, 1117