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Probing neutron star evolution using cyclotron lines

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Abstract. Accretion of matter on a neutron star is believed to cause a significant reduction of its magnetic field strength. One popular mechanism for this is the burial of the field under the highly conducting accreted matter. For this to occur, matter in the magnetically confined accretion column on the polar cap of a strongly magnetized star should spread over the stellar surface while causing large distortions in the field structure. Phase resolved cyclotron line spectroscopy can probe these distorted magnetic field structures and help examine such evolution. India's upcoming satellite ASTROSAT will be uniquely capable of carrying out such observations. This talk will discuss some of the relevant theoretical models and their predictions.

Keywords : X-rays: binaries – acceretion – magnetic fields – line : formation

1. Introduction

The accreting neutron star population can be broadly divided into two categories: the High-Mass X-ray Binaries (HMXB), where the donor star is of several solar masses, and the Low-Mass X-ray Binaries, in which the donor star mass is typically less than the mass of the neutron star. The neutron stars of the latter category have rather low strength of the magnetic dipole moment (surface field $\sim 10^8 - 10^9$ G), while the HMXBs appear to have magnetic moments similar to isolated radio pulsars ($\sim 10^{12}$ G). Observations suggest that prolonged accretion on the neutron star might result in its magnetic field strength being reduced, although there is no consensus as yet regarding the mechanism for this. A popular belief is that the magnetic field of the neutron star is buried under the accretion flow as the matter spreads over the star's surface (e.g. Bisnovatyi-Kogan & Komberg 1974; Romani 1990; Konar & Choudhuri 2002; Payne & Melatos 2007 and references therein). However this could be thwarted by plasma instabilities to which the flow is susceptible. A detailed analysis of this, including instabilities, is yet to be made.

In this presentation we deal with magnetostatic balance of accretion mounds at the polar cap regions of HMXBs, and estimate the amount of distortion of local magnetic field that may be caused in order to support the weight of the accretion mound. The amount of matter that can be supported in such a mound, and hence the degree of distortion of the local field, would depend on when instabilities become important. If an estimate of the field distortion can be obtained from observed spectra, then it would shed some light on the role such instabilities may play in the polar cap region.

One of the ways to probe the magnetic field structure at the polar cap would be by rotation phase-resolved spectroscopy of the cyclotron resonance scattering features produced in this region. The energy of these lines is directly related to the local magnetic field ($E_{\rm cyc} = 11.6(B/10^{12}$ G) keV to the first order). The HMXBs under discussion are X-ray pulsars: the X-ray emitting polar hot spots going in and out of view as the star spins. Tracking the change in cyclotron line energies and profiles as a function of the spin phase of the star could lead to a magnetic tomography of the emission region. New generation X-ray missions, including India's ASTROSAT satellite, will have the capability to study the cyclotron features with high sensitivity, enabling a serious phase-resolved study. The effects discussed here are likely to become observable when these new missions begin to operate.

2. Structure of the accretion mound

We now investigate the structure of an accretion mound located in a polar cap region of radius 1 km, on a $1.4M_\odot$ neutron star of 10 km radius. The mound is considered axially symmetric, with its symmetry axis along the z axis of our cylindrical (r, θ, z) coordinate system. Introducing a Flux function $\psi(r, z)$ which gives the poloidal flux passing through a circle of radius r at a given z, we can write the equation of magnetostatic balance as

$$\nabla p - \rho \mathbf{g} + \frac{\Delta^2 \psi}{4\pi r^2} \nabla \psi = 0 \tag{1}$$

where the operator Δ^2 stands for $\Delta^2 \equiv r\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}\right) + \frac{\partial^2}{\partial z^2}$ and the acceleration due to gravity $\mathbf{g} = g\hat{\mathbf{z}}$ is assumed to be constant. Using an adiabatic equation of state $p \propto \rho^\gamma$ and writing the density distribution in the mound in the form $\rho \propto [Z_0(\psi) - z]^{1/(\gamma-1)}$, the magnetostatic balance equation (1) can be cast in the form of a Grad-Shafranov equation (Hameury et al. 1983):

$$\frac{\Delta^2 \psi}{4\pi r^2} = -\rho g \frac{dZ_0}{d\psi} \tag{2}$$

We solve eq. (2) numerically for different specifications of mound height function $Z_0(\psi)$. For most of our work we specify this in the form of a central mound height Z_m and a parabolic fall off at higher values of ψ. Far from the mound the magnetic field is assumed to be uniform, and at the bottom of the mound (the interface with the solid crust) we use line-tying condition of the same uniform field. To support the pressure of the mound, magnetic field becomes distorted through the mound, larger mound heights Z_m causing higher distortion. Figure 1 shows the comparison of two cases, for mound heights of 70 and 98 m respectively. The density distribution of these

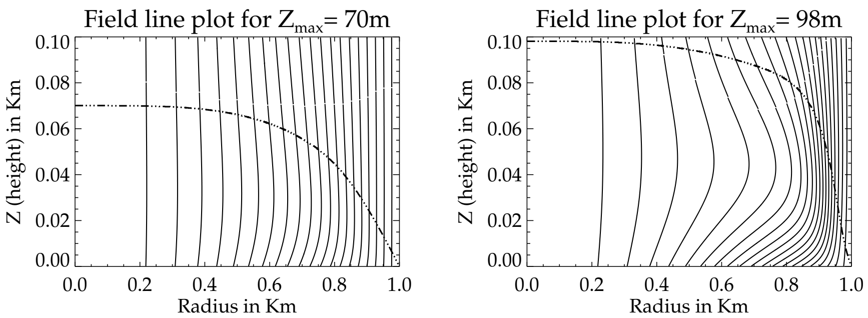

Figure 1. Field line distortions to support a magnetically confined plasma mound at the polar cap of a neutron star. The dash-dotted line defines the top of the mound surface. The rise in the local field strength (proportional to field line density) is clearly visible towards the periphery of the mound. The figure on the left is for a central mound height of 70 m and the one on the right is that for 98 m. The composition of the plasma is assumed to be pure hydrogen in this run

mounds are such that they are optically thick to X-ray radiation, the cyclotron line formation region lying within a few mm of the top surface. The emerging cyclotron line spectrum will therefore bear the signature of the magnetic field distribution at the top surface. As can be seen from figure 2, the field strength could vary by a factor of several tens to hundreds of percent across the top surface of these mounds, much larger than at most a few per cent variation expected from a pure dipole field.

3. Cyclotron spectra

We have seen that matter accreting on the polar cap of a neutron star can accumulate in magnetically supported mounds and such mounds can cause significant distortion of the local field structure. This distorted magnetic structure can be probed by sensitive, spin phase resolved cyclotron line spectroscopy. Such observations would also shed light on the manner in which matter spreads from the mound to the rest of the neutron star surface, and thus on the process of "field burial" and the long-term evolution of the magnetic field. Detailed predictions of cyclotron spectra from accretion mounds described above may be found in our recent and forthcoming work (Mukherjee & Bhattacharya, 2012; Kumar, Mukherjee & Bhattacharya, in preparation).

Cyclotron lines have been detected in the X-ray spectra of over a dozen HMXB pulsars (see reviews by Heindl et al. 2004, Mihara et al. 2007). However, phase resolved study has so far been possible for only a small number of these sources, and that too with limited sensitivity. The results show line energy variation by several tens

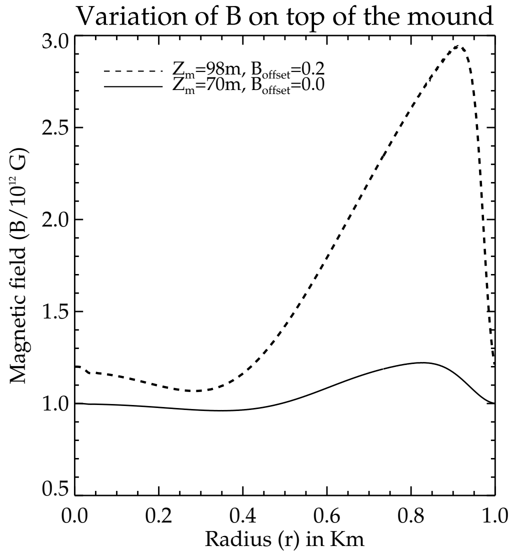

Figure 2. The radial profile of the magnetic field strength across the mound surface for the two cases of central height, 70 m and 98 m respectively. The variation of field strength across the surface is $\sim$ 20% for a 70 m mound and $\sim$ 300% for a 98 m mound. This is much larger than the expected variation of a pure dipole field over this area, which is less than $\sim$ 2%.

of percent as a function of spin phase in some of the sources, indicative of the variation of the local magnetic field strength by a similar amount in the line forming region. However the observations are still too premature to be conclusively used for mapping the magnetic field distribution. A significant improvement in sensitivity in hard-Xray bands is required for making further progress. India's ASTROSAT mission, due to be launched in 2012, will improve the sensitivity by about an order of magnitude in this band compared to the currently operating missions and will make important contributions to this study.

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