Magnetic field in neutron stars: from interior to surrounding accretion discs

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New perspective on a *magnetic field*

Outline

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   - Model and equations
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2. Magnetic field deformation in ADs
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   - Model and equations
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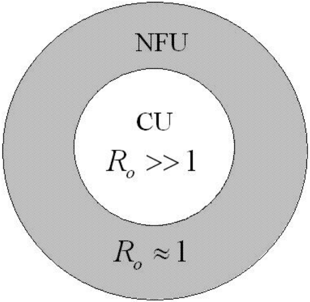
Unification scenario in neutron stars

- Nowadays we observe several different classes of neutron stars (NSs) with different properties: standard radio pulsars, soft gamma repeaters and anomalous X-ray pulsars, . . .
- Is a unified model possible? How to explain the differences?
  1. Single evolution path (classes are different stages)
  2. Multiple paths (same origin, different paths)
- Before the creation of a stable NS a proto-NS (PNS) is formed
- Plasma inside PNSs is turbulent and develops two hydrodynamical instabilities (convective- and neutron finger- instability) that influence the evolution of the magnetic field
- The neutron finger instability can activate a mean field dynamo, that can amplify any seed field to produce a large scale magnetic field

Model and equations

- The dynamo is active only in the neutron finger unstable zone (small Rossby number)
- We follow the magnetic field time evolution by solving the induction equation for mean fields (includes turbulence), within the kinematic approximation
- Magnetic feedback on plasma is included through a quenching function, $\psi = \psi(1/B^2)$



$$\partial_t B = \nabla \left(v \times B + \psi\, \alpha B - \eta \nabla \times B \right)$$

Results

We have proved the feasibility of the scenario with a 1D model:

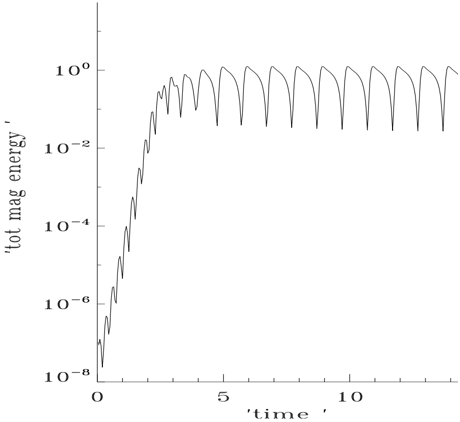
1. Time evolution: growth phase and saturation. Steady configuration can be either constant or oscillatory
2. Activating the dynamo: it depends on period and differential rotation. There is a critical period below which the dynamo is always active, $P_c \sim 500$ ms
3. Final field: below P_c non-magnetised NS are formed, above P_c there is a large range that depends on P and Omega: $B_{\mathrm{pol},\,\phi} \propto P^{\delta} \Delta\Omega^{\gamma}$

We are now studying a more complex axisymmetric 2D model with a more realistic rotational profile in spherical coordinates:

- Explore the 3D phase space $(P,\ \Omega,\ \partial_r\Omega)$, study the growth rate and the topology of the magnetic field
- First results confirm the existence of a critical period and also show some new features (e.g. inactivity islands, non trivial dependence on Ω)

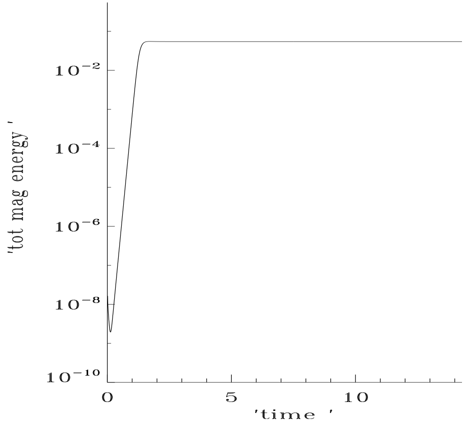
Results (2D): time evolution

Example of oscillatory dynamo



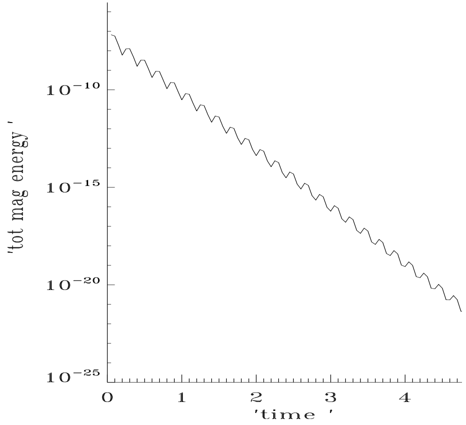
Results (2D): time evolution

Example of constant dynamo



Results (2D): time evolution

Example of non active dynamo



Results (2D): magnetic field structure

(Loading animation: $B_{\rm pol}$ vectors)

Results (2D): magnetic field structure

(Loading animation: B_ϕ contours)

Summary

Our (ambitious) goal is to explain neutron star magnetic differences on the basis of a process happening during the star formation phase

- All NSs go through the proto-NS phase, during this phase their interior is unstable and can activate a mean field dynamo
- This phase lasts about 40 s, at the end of this time the field remains frozen with the newly born NS, so that the magnetic properties of a NS at birth are those at the end of the PNS phase
- The field time evolution is governed by the dynamo and its final configuration depends on the initial conditions (period and differential rotation of the PNS)
- We find quite a large critical period, so that the dynamo should be active in the majority of PNSs, and the final intensity range is quite wide

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Accretion discs around neutron stars

- Magnetic fields play crucial roles in accretion discs, e.g. MRI and jets

But this is not the whole story ...

- they can strongly influence the spin history of the central object, because they create a connection between large part of the disc and the star
- We observe different kinds spin history: constant spin up, constant spin down and also alternation of the two.
- Other properties may change at the same time, e.g. luminosity, spectral state and accretion rate

Magnetic torque and millisecond pulsars

We focus on millisecond pulsars, which are thought to be old pulsars spun up ("recycled") by an accretion disc

- In the recycled scenario one calculates the total torque exerted by the disc on the star. To reconcile with observations it is fundamental to include the magnetic contribution to the total torque.
- Nowadays models from the 80's are still being used, where: (1) the poloidal component of the magnetic field is assumed to be a dipole, (2) the disc is taken thin and (3) the velocity field has only the ϕ component (Keplerian)
- Within these models one obtains:

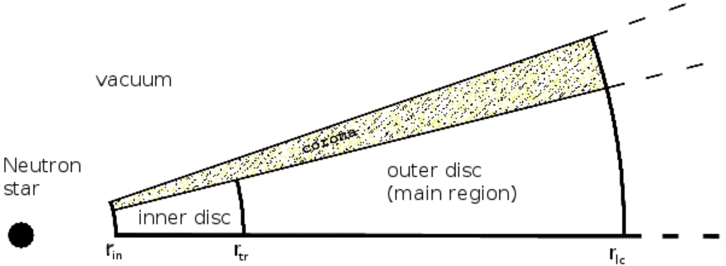
$$B_\phi \propto \Delta\Omega \, B_z \qquad\qquad \Gamma_B \propto B_\phi \, B_z \, \varpi / h$$

- In this picture the disc inward of corotation spins the star up, while the part outward of corotation spins it down. Very plausible, but too simplified.

We aim to improve the 80's models by means of a semi analytic procedure

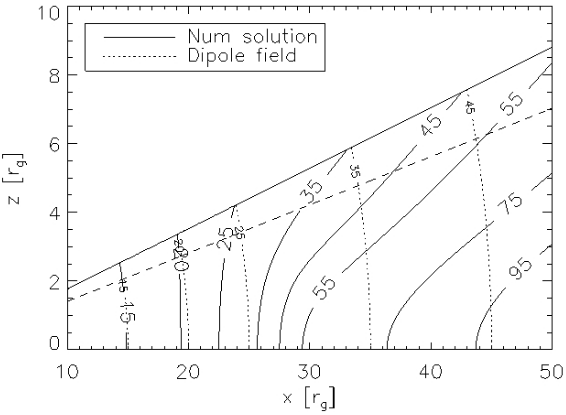
Model description

1. Stellar magnetic field is dipolar with axis aligned with rotation
2. Corona above and below the disc, as transition to vacuum BC
3. Stationary conditions and axisymmetry
4. Kinematic approximation (with α-disc)
5. We solve the induction equation numerically (Gauss-Seidel)
6. Fully 2D and all components of $\vec{B}$



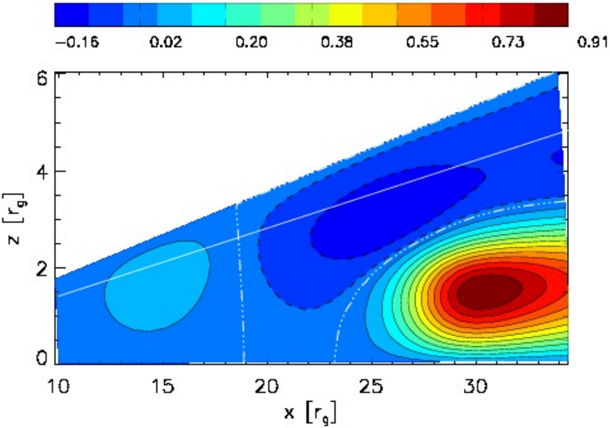
Results - Poloidal field lines

Field lines pushed inwards, magnetic field amplification



Results - Toroidal field contour

B_ϕ is zero at corotation, big positive peak outwards



Results

We have analysed several configurations with different values of velocity and turbulent diffusivity

- Deformation are not homogeneous, we thus generalise the magnetic Reynolds number and introduce a magnetic distortion function:

$$R_m = \frac{L_0\, v_0}{\eta_0} \qquad\qquad D_m = \frac{r_g\, \sqrt{v_r^2 + v_\theta^2}}{\eta}$$

  Deformations are large in regions where $D_m > 1$ and small in the others; field lines accumulates where D_m changes from small to large values

- Peaks in the B_ϕ profile come from two parts:
  (1) $\Delta\Omega \cdot B_\theta$, as in the 80's model (2) $\partial_r D_m$, new term
- Our (semi) analytic expression for the toroidal component:

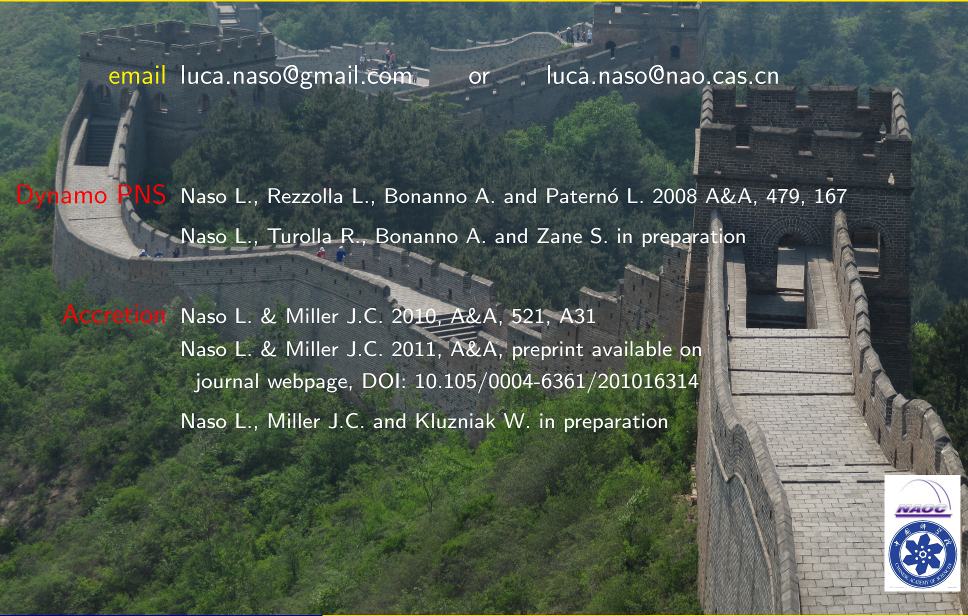
$$B_\phi = \frac{\partial_r(r v_\phi B_r) + \partial_\theta(v_\phi B_\theta)}{r} \cdot \frac{r_g^2}{\eta_T} \qquad [B_\phi \propto \Delta\Omega \cdot B_z]$$

Conclusions

Magnetic fields strongly influence the spin history of central object, having the correct profile is fundamental to properly calculate the magnetic torque

- Polidal magnetic field lines are pushed inwards by the accreting plasma and they can accumulate in the inner part of the disc
- This behaviour is independent from any ϕ quantity and is well described by the magnetic distortion function
- A toroidal component of the magnetic field arises because of the rotation of the disc plasma
- B_ϕ profile depends both on the angular rotation of the plasma and on the deviation away of the poloidal component from the dipole.

For further information and discussions



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