Magnetic Field Evolution for Accreting Neutron and Quark Stars

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Abstract

In this work we studied the evolution of the magnetic field for an accreting neutron star as a function ohmic diffusion and as a function of the convective transport of the accreted matter through the stellar crust.

We assumed an appropriate vector potential in order to get a dipolar magnetic field and we solved the resulting field evolution equation numerically by the Crank-Nicholson method for a 1.4 solar mass hadronic neutron star with approximately 11 km of radius.

We also assumed a constant accretion rate. For regions of low density (near the surface) and very high density (near the core) the diffusive process is more important; for intermediate regions, the convection plays a major role.

For constant accretion rate, the field intensity suffers a rapid decay down to a constant value.

1. Accretion and the Transport of the Accreted Matter

In this work we study the magnetic field evolution for an accreting neutron star .

Assuming that the mass flow onto the neutron star crust is constant and spherically symmetric, we get

$$\dot{M}dt = 4\pi r^2 \rho(r) dr,$$

where $\dot{M}$ is the accretion rate and $\rho(r)$ is the density as a function of the radial coordinate, r, from which we get the velocity of the material penetrating the crust:

$$\vec{v}(r) = -\frac{\dot{M}}{4\pi r^2 \rho(r)}\hat{r}.$$

2. Density Profile of the Neutron Star

The neutron star model assumed here has three different characteristic regions: the outer crust, the inner crust and the core.

Each region is described by a specific Equation of State (EoS) and the combination used in this work is Baym, Pethick & Sutherland (BPS) for the outer crust [1]; Negele & Vautherin (NV) for the inner crust [2] and Wiringa, Fiks & Fabrocini (WFF) for the core [3].

Knowing the EoS of the neutron star we can find the density profile solving the Tolman, Oppenheimer and Volkoff equations (TOVs).

3. Conductivity and Temperature of the Neutron Star

Other important parameters for calculating the magnetic field evolution are the conductivity and the temperature of neutron star.

The temperature for an accreting neutron star is given by

$$\log T = 0.397 \log \dot{M} + 12.35,$$

for the accretion rate in the range 10^{-15} M$_\odot$/yr $\dot{M} < 2\times10^{-10}$ M$_\odot$/yr [5].

For the regions where the temperature of the neutron star is higher than its melting temperature, the crust is in liquid state; otherwise, the crust is in solid state. In the figure 1 we compare the melting temperature as a function of density of the neutron star with three different possible constant values for the neutron star temperature.

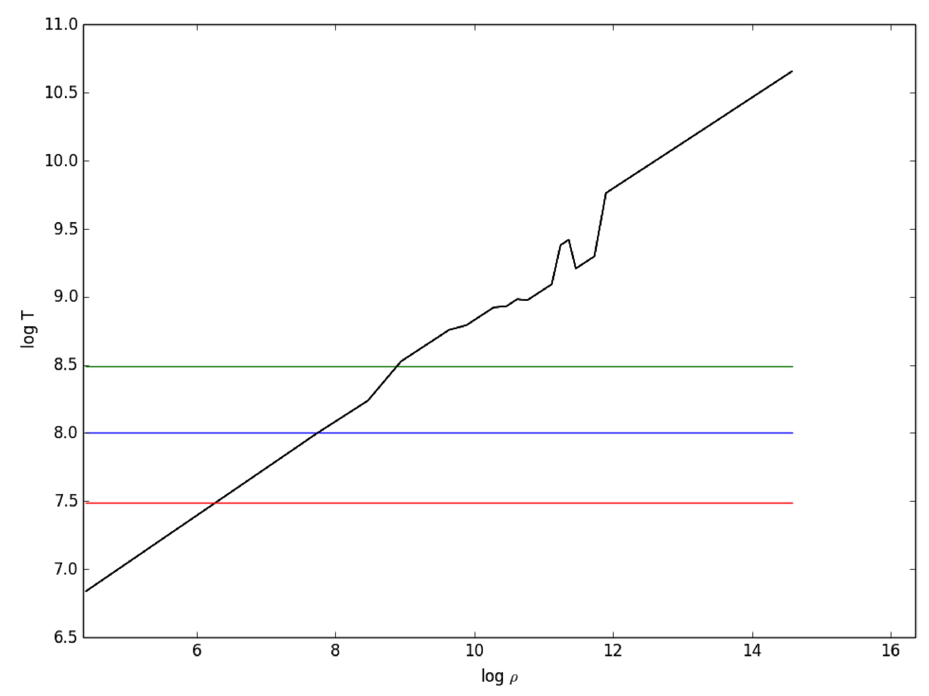

Figure 1: *Comparison between the temperatures T = $10^{7.5}, 10^8$ e 10^8 and the melting temperature of a neutron star.*

For the liquid part of the neutron star crust the conductivity is given by

$$\sigma_{liq} = 8.53\times10^{21}\frac{y^3}{Z\Lambda_{Coulomb}(1+y^2)},$$

where $y = \left(\frac{Z\rho_6}{A}\right)^{1/3}$.

For the solid region the conductivity is

$$\sigma_{solid} = \frac{1}{\sigma^{-1}_{phonon} + \sigma^{-1}_{impurity}},$$

where

$$\begin{cases} \sigma_{impurity} = 8.53\times10^{21} xZ/Q/s \\ \sigma_{phonon} = 1.24\times10^{20}\frac{x^4}{uT_8}\frac{(u^2+0.0174)^{1/2}}{(1+1.1018x^2)I_\sigma} \end{cases}$$

where

- $u = \frac{2\pi}{9}(\log\rho - 3)$,
- T_8 is the temperature in units of 10^8 K,
- I_σ is a function of density, Z and A [4].

The total conductivity is shown in figure 2

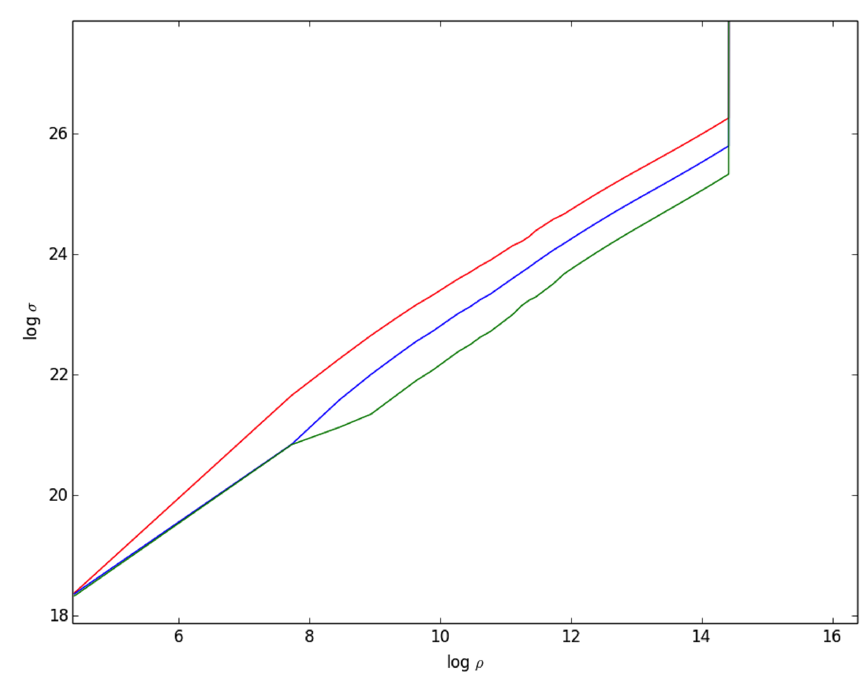

Figure 2: *Conductivity profile for the three temperatures cited in figure 1.*

4. Magnetic Field Evolution

We know that the induction equation for the magnetic field evolution is

$$\frac{\partial\vec{B}}{\partial t} = \vec{\nabla}\times(\vec{v}_e\times\vec{B}) + \frac{c^2}{4\pi}\vec{\nabla}\times\left(\frac{1}{\sigma}\vec{\nabla}\times\vec{B}\right),$$

where the first term corresponds to the convective transport and the second term corresponds to the Ohmic diffusion.

The magnetic field is assumed to be dipolar and to get this form we chose a potential vector $\vec{A} = (0,0,A_\phi)$ where $A_\phi = \frac{g(r,t)\sin\theta}{r}$. Knowing that $\vec{B} = \nabla\times\vec{A}$ we obtain the g-function evolution

$$\frac{\partial g(x,t)}{\partial t} = v(x)\frac{\partial g(x,t)}{\partial x} + S(x,t)\left(\frac{\partial^2 g(x,t)}{\partial x^2} - \frac{2g(x,t)}{x^2}\right),$$

where

$$\begin{cases} x = \frac{x}{R} \\ v(x) = \frac{v(r)}{R} \\ S(x,t) = \frac{c^2}{4\pi\sigma(r,t)R^2} \end{cases}$$

For an isolate neutron star, the magnetic field decays due to Ohmic dissipation only and its evolution is shown in figure 3.

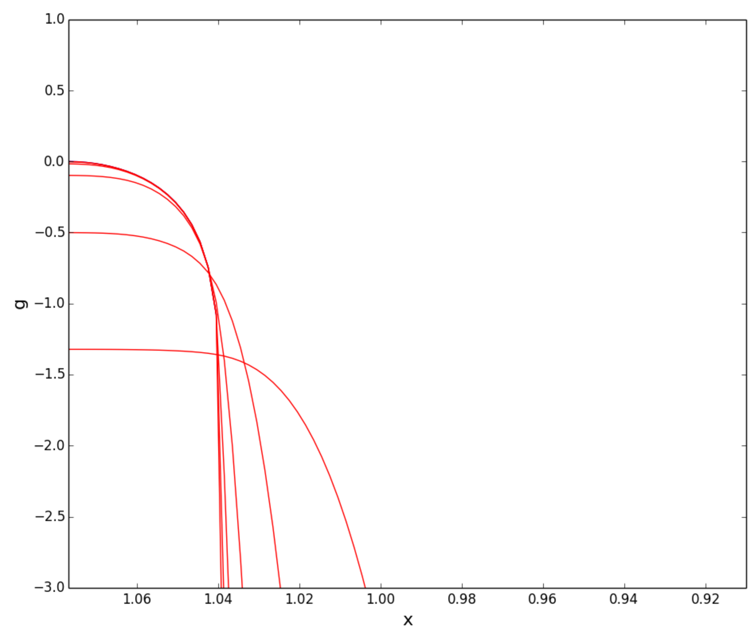

Figure 3: *g-profile spanning 10^6 years for a isolate neutron star due to Ohmic diffusion. The curves shown at intermediate times correspond to t = $10, 10^2, 10^3, 10^4, 10^5$ e 10^6 years. The first point in the x-axis corresponds marks the surface of the star.*

However, when the neutron star is in a binary system accretion matter, the decay of the g-function is due to Ohmic diffusion coupled with convective transport of the accreted mattern through its crust. This decay is shown in figure 4.

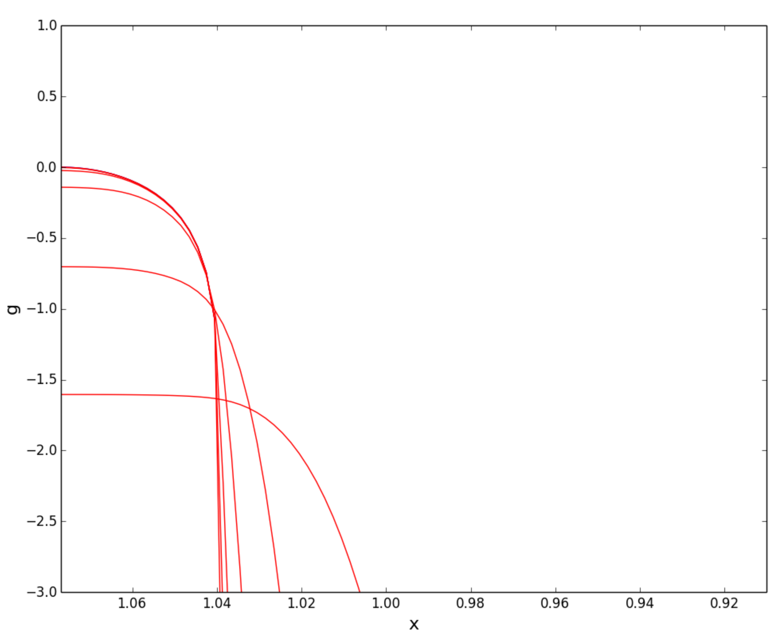

Figure 4: *g-profile spanning 10^6 years for a neutron star accreting matter from a companion star. The decay is due to a coupling of Ohmic diffusion and convective transport of the accreted matter. The curves shown at intermediate times correspond to t = $10, 10^2, 10^3, 10^4, 10^5$ e 10^6 years. The first point in the x-axis corresponds to the surface of the star.*

Comparing the figures 3 and 4 we can see that the g function decays faster when the neutron star is in a binary system where accretion takes place. Therefore, the magnetic field decays faster for accreting neutron stars.

5. Prospects

The next step in this work will be to evolve the magnetic field up to 10 Gyr. After, we will evolve the magnetic field for a time dependent accretion rate where the accretion rate itself is in the range 10^{-15} to 10^{-10} solar masses per year.

We also intend to calculate the magnetic field evolution for a accreting quark star with normal crust and compare the results.

References

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