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Hall drift in the crust of neutron stars - necessary for radio pulsar activity?

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Abstract. The radio pulsar models based on the existence of an inner accelerating gap located above the polar cap rely on the existence of a small scale, strong surface magnetic field B_s. This field exceeds the dipolar field B_d, responsible for the braking of the pulsar rotation, by at least one order of magnitude. Neither magnetospheric currents nor small scale field components generated during neutron star's birth can provide such field structures in old pulsars. While the former are too weak to create $B_s \gtrsim 5 \times 10^{13}$G $\gg B_d$, the ohmic decay time of the latter is much shorter than 10^6 years.
We suggest that a large amount of magnetic energy is stored in a toroidal field component that is confined in deeper layers of the crust, where the ohmic decay time exceeds 10^7 years. This toroidal field may be created by various processes acting early in a neutron star's life. The Hall drift is a non-linear mechanism that, due to the coupling between different components and scales, may be able to create the demanded strong, small scale, magnetic spots.
Taking into account both realistic crustal microphysics and a minimal cooling scenario, we show that, in axial symmetry, these field structures are created on a Hall time scale of 10^3-10^4 years. These magnetic spots can be long-lived, thereby fulfilling the preconditions for the appearance of the radio pulsar activity. Such magnetic structures created by the Hall drift are not static, and dynamical variations on the Hall time scale are expected in the polar cap region.

1. The basic idea.

The Partially Screened Gap Model relies on an intimate interplay of the cohesive energy in the polar cap surface layer and the corresponding surface temperature T_s as well as on the partial screening by the thermal outflow of iron ions (Gil et al. (2003)). Both quantities depend on the local surface field strength B_s. The condition for the existence of an accelerating gap has been calculated by Medin & Lai (2007). The balance of heating by the bombardment with ultrarelativistic particles and cooling by radiation returns for typical radio pulsar parameter $T_s \gtrsim 10^6$ K Gil et al. (2003), a significantly higher value than the cooling age predicts. In order to enable the creation of a gap for such high T_s, B_s has to be larger than 5×10^{13} G, perhaps even larger than 10^{14} G. Simultaneous X-ray and radio observations with X-ray spectra that can be fitted by blackbody radiation (Kargaltsev et al. (2006); Zhang et al. (2005)) support these estimates. Though these fits have to be considered with caution (see ERPM talk of W. Hermsen) they may be indicating that the base of the open field lines on the stellar surface (heated to temperatures above 10^6 K) is much smaller than the conventional polar cap (Ruderman & Sutherland (1975)). Flux conservation arguments lead to $B_s \gtrsim 5 \times 10^{13}$ G $\gg B_d \sim 5 \times 10^{12}$ G (for a typical radio pulsar).

In order to allow an efficient electron-positron pair creation rate within the accelerating gap, the curvature radius of the magnetic field lines must be $R_{B_s} \ll R_{B_d} \sim 100$ km (Ruderman & Sutherland (1975)). This is valid when either curvature radiation or inverse Compton scattering are the dominating processes (Melikidze et al. (2000),Szary et al. (2011)). Polar cap surface fields of the required strength and curvature cannot be present since the birth of the neutron star, because the electric conductivity during the first $\sim 10^4$ yr is relatively low and, for small-scale structures is $\lesssim 1$ km, the ohmic decay time in the subsurface crustal layers is typically only a few 10^2 - a few 10^3 yrs. Therefore, the demanded B_s has to be (re-)created and maintained over the lifetime of radio pulsars, i.e. $\sim 10^6 - 10^7$ yr. Therefore, there must be a large reservoir of magnetic energy, stored in regions where it can survive for $\gtrsim 10^6$ yr, which, at some point over the lifetime of radio pulsars, can be tapped for forming this B_s.

Since magnetospheric currents are not a plausible mechanism to create the demanded B_s - structures (Hibschman & Arons (2001)), the Hall drift of the crustal magnetic field turns out to be a possible alternative to explain the existence of the of small scale, strong surface fields. We propose that the energy reservoir is a large scale crustal toroidal field whose maintaining currents circulate in deeper layers, where the high electric conductivity ensures a sufficiently long lifetime. Due to the non-linear interaction of the crustal and/or core based poloidal field $\sim B_d$ with the toroidal crustal field, a magnetic spot in the vicinity of the polar cap can be created.

2. Results from simulations.

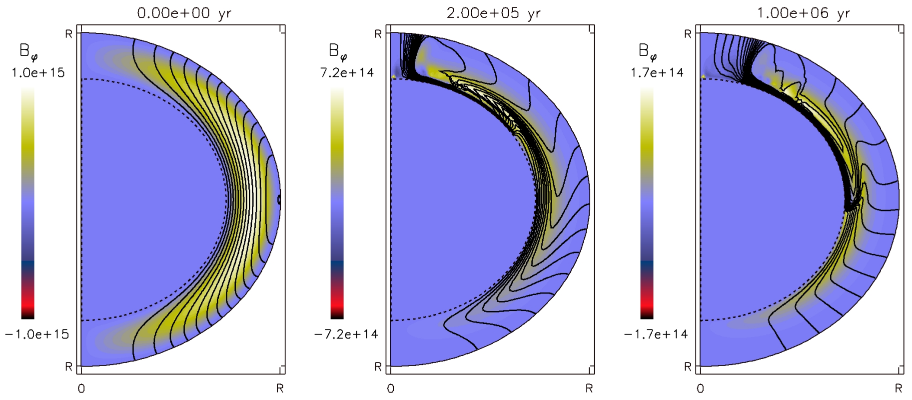

Figure 1. Structure of the crustal magnetic field at $t = 0$ (left), after 2×10^5 (middle) and after 10^6 yrs (right). The poloidal field is shown by solid lines, the isolines of the toroidal field are color coded. The crustal region has been stretched a by factor of 4 for visualization purposes. The complete movie showing the field dynamics is available at *http://personal.ua.es/en/daniele-vigano/hall-pulsar.html*

The evolution of the magnetic field in the crust, where electrons are the only carriers of the field generating electric currents, is described by the Hall induction equation. For details see Pons & Geppert (2007). The Hall drift can generate very small scale structures, such as current sheets and shock-like patterns, out of a large scale field. A numerical code based on a finite difference scheme and non-local boundary conditions (Viganò et al. (2012)) has been used to follow the evolution of the magnetic field under typical conditions, with realistic microphysics (Aguilera et al. (2008)) and for the minimal cooling scenario (Page et al. (2004)).

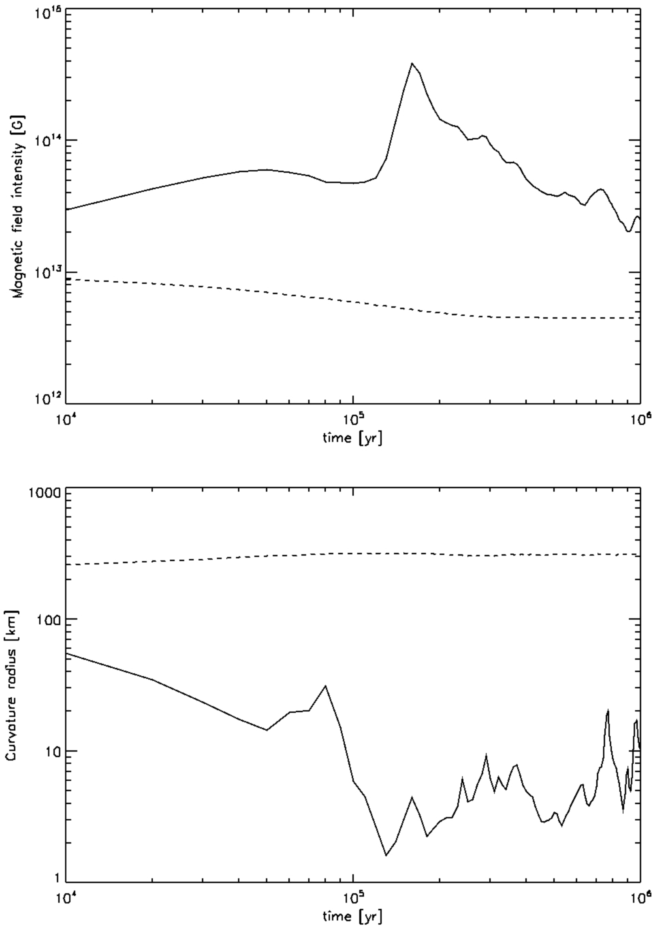

Figure 2. Temporal evolution of B_s (left) and R_{B_s} (right) near the north pole, considering only Ohmic dissipation (dashed) or including the Hall term (solid). We show averages of the numerical values of B_s and the minimum of R_{B_s} in the region $1^\circ - 5^\circ$ from the north pole.

We assume an initial field configuration as depicted in the left panel of Fig. 1. MHD equilibria suggest that the toroidal field is concentrated in an equatorial belt, filling only a small part of the crust volume. However, there are mechanisms conceivable (e.g. small scale dynamos, magneto-rotational and thermoelectric instabilities) that can create strong internal fields soon after a neutron star's birth. In some cases, the crustal field can have a large toroidal component that fills most of the crust volume, which results in a strongly peaked temperature distribution, consistent with the observed large pulsed fraction of Kes 79 (Shabaltas & Lai (2012)).

Fig. 1 shows the structure of the crustal field after 2×10^5 and 10^6 yrs. The strong, small scale field structures are formed within a few 10^4 yr and can survive over a million years because of the relatively low temperature (high conductivity), in contrast with the fast dissipation of initial structures in very young, hot neutron stars. The temporal evolution of B_s and R_{B_s} near the north pole is shown in Fig. 2. After $\sim 10^5$ yrs $B_s \gtrsim 10 \times B_d$ there; the radius of field line curvature is about two orders of magnitude smaller than in case of a purely resistive field evolution. Obviously, the Hall drift introduces another time scale into the polar cap dynamics that is neither determined by the pulsar rotation nor by the $\vec{E} \times \vec{B}$-drift but solely by the non-linear evolution of the crustal magnetic field. We must note that the large magnetic Reynolds numbers close to the polar surface results in some numerical noise that makes us consider the absolute values of B_s and R_{B_s} with caution.

3. Conclusion

Our main conclusion is, therefore, that the Hall drift is a viable process, that might create both on a correct time scale and on proper scale lengths the surface magnetic field configurations that enable a neutron star to appear as radio pulsar. Although the model is limited to the 2D, axially symmetric case, so that no ”real” spots, limited both in meridional and azimuthal direction, can arise, the results are promising and should motivate further investigations in this field.

References

Aguilera, D. N., Pons, J. A., & Miralles, J. A. 2008, A&A, 486, 255. `0710.0854`

Gil, J., Melikidze, G. I., & Geppert, U. 2003, A&A, 407, 315. `arXiv:astro-ph/0305463`

Hibschman, J. A., & Arons, J. 2001, ApJ, 546, 382. `arXiv:astro-ph/0008117`

Kargaltsev, O., Pavlov, G. G., & Garmire, G. P. 2006, ApJ, 636, 406. `arXiv:astro-ph/0510466`

Medin, Z., & Lai, D. 2007, MNRAS, 382, 1833

Melikidze, G. I., Gil, J. A., & Pataraya, A. D. 2000, ApJ, 544, 1081. `arXiv:astro-ph/0002458`

Page, D., Lattimer, J. M., Prakash, M., & Steiner, A. W. 2004, ApJS, 155, 623. `arXiv:astro-ph/0403657`

Pons, J. A., & Geppert, U. 2007, A&A, 470, 303. `arXiv:astro-ph/0703267`

Ruderman, M. A., & Sutherland, P. G. 1975, ApJ, 196, 51

Shabaltas, N., & Lai, D. 2012, ApJ, 748, 148. `1110.3129`

Szary, A., Melikidze, G. I., & Gil, J. 2011, ArXiv e-prints. `1108.4560`

Viganò, D., Pons, J. A., & Miralles, J. A. 2012, ArXiv e-prints. `1204.4707`

Zhang, B., Sanwal, D., & Pavlov, G. G. 2005, ApJ, 624, L109. `arXiv:astro-ph/0503423`