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EVOLUTION OF PULSARMAGNETISM BY VIRTUE OF A FARADAY DYNAMO MECHANISM

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ABSTRACT

The evidence that radio-pulsars are slowed-down and Röntgen pulsars accelerated predominantly by magnetic torques is now very strong. Angular momentum is transferred away from the neutron star to the velocity-of-light cylinder[1,2] or from the Alfven-cylinder down to the neutron star[3,4] by means of a magnetic spring the physical origin of which is an appropriate current flowing along the magnetic field lines. As this current must be closed at the neutron star's surface and no Hall-field can be built-up a Faraday dynamo mechanism is set up. It is pointed out that this mechanism could switch-off a radio pulsar or turn-on a Röntgen pulsar. Many disconcerting pulsar observations could thus be explained, if radio pulsars can be reactivated in the galactic plane by means of accretion of matter in dense clouds and if Röntgenpulsars must first create a sufficiently strong magnetic field to function as a regularly pulsed emitter.

INTRODUCTION

Soon after the identification of pulsars with neutron stars[5,6] and based on a rather small sample of radio pulsars it was pointed out[7,8] that the observation of absence (which at that time might also have been absence of observation) of long period pulsars could be understood if one assumed that the magnetic field decayed on a time-scale of some My. In fact the radius R of a neutron star is so small, typically $R \simeq 10^6$ cm, that the decay time of the magnetic field τ_d, due to Ohmic dissipation

$$\tau_d = \frac{4\sigma R^2}{\pi c^2} \qquad (1)$$

amounts to some My, if the conductivity of the neutron star's material is $\sigma = 10^{23}$ sec^{-1}, and for non-degenerate matter this would be a rather large value. However the matter of a neutron star is extremely degenerate and due to the Pauli principle the conductivity σ is many orders of magnitude larger in the main body of a neutron star[9]. In fact in some part of the neutron star the protons may actually form a type II superconductor[10]. Consequently only in the crust of a neutron star can the magnetic field decay, typically within some 10 My if the neutron star is hot enough[11,12] (or if the crust material is very impure), and this would not lead to any appreciable reduction of the neutron star's dipole magnetic moment[11]. Unimpressed by such theoretical considerations observers continued to discuss their observational results in terms of magnetic field decay[13,14] and this essentially until today[15].

How do pulsars turn-off then, if magnetic field due to Ohmic dissipation is not possible? Three further ideas have been offered. The first is simply a variant of the magnetic field decay hypothesis. It was pointed out that once the current in the crust has decayed the liquid interior would allow the magnetic dipole field to reorient[16] itself lowering thereby the magnetic energy and form a quadrupole field. This reorientation of the poloidal magnetic field could however be impeded[16] by the presence of strong toroidal fields which are expected to be produced at the pulsar's birth[17] or in the preneutron star stage[18]. The second is based on the fact that external or internal torques may lead to considerable alignment[19,20] of the pulsar's spin axis withe the axis of the magnetic field. While there is probably agreement between pulsar theorists that the angle between dipole axis and spin axis plays an important role in pulsar evolution[21,22,23] it is also evident that it cannot explain pulsar turn-off alone. Therefore some other mechanism must be at work. In line with work by Sturrock[24] and others[25,26] Ruderman and his group have developed the idea that sparking in gaps is responsible for the coherent radio emission of radiopulsars and that the process depends sensibly on surface temperature and rotation period[22]. The following discussion is also in line with these considerations and stresses, as will be seen, the importance of the surface temperature. Summarizing the present state of the art one may say (with respect to the radiopulsars) that a number of models have been developed which can explain one or a few observed facts but none can satisfactorily explain all or even most of what has been observed. However valuable extra information about neutron stars has come from X-ray observations, calling into doubt the simple picture outlined above. There is (theoretical) evidence[27] that Her X-1, which has a strong magnetic field as inferred from the cyclotron line[28] and which is quite hot (which should enhance magnetic field decay)is some 500 My old and this argues strongly against magnetic field decay. Furthermore many cyclotron lines have by now been detected in γ-ray bursters and these are probably old, occasionally accreting (binary?) neutron stars. Of special significance (if correctly interpreted as an old neutron star[21]) is the γ-ray transient[30] with a period of 8 s. Here the most likely explanation is the infall of a comet[31] on a strongly magnetized neutron star rotating with a period of 8 s, arguing both against magnetic field decay and aligment. It is noteworthy that the possibility of such an extreme event was considered[31] well before the actual discovery, demonstrating that here also theory had some predictive power. While there is therefore some evidence that old neutron stars posses non-aligned strong magnetic fields there is also ample evidence to the contrary. The group of RÖntgen-stars which reveal a magnetic field is quite small, the great majority either conceal their magnetic fields or do not have a strong magnetic field. To these belong all the bursters, which have been studied especially carefully[33] . While these disconcerting observations are hard to reconcile with conventional ideas about neutron stars and their magnetic fields the following observational facts show that a radically new idea for their explanation is needed. Improved pulsar statistics[34] have fully confirmed the early conclusions[35] that pulsars are predominantly born in the galactic plane, that they have larger peculiar velocities (amounting to some 10^{47} erg of kinetic energy) and that the inferred kinetic ages do not exceed some My. There is therefore every theoretical and observational evidence that neutron stars must be born in supernovae.

No neutron stars have however been detected at the sites of young supernovae[36], a fact which is especially disconcerting if one recalls that the conventional interpretation of the pulsar data leads to the conclusion that the formation-rate of pulsars is larger than the ocurrence-rate of supernovae[37] even if every supernova would lead to the formation of a neutron star (which it does not). Dismissing the possibility that pulsars are born by the dozen, for which there is no observational evidence[38], the only way to explain all these findings is that the magnetic fields of neutron stars evolve as does e.g. the magnetic field of the earth.

The idea that the magnetic field of the earth was fossil (i.e. due to remanent magnetization) was given up around the turn of the century. Through discovery of numerous reversals of the geomagnetic field throughout the geological history of the Earth it became clear that the cause of geomagnetism is a dynamic one and that motions in the liquid core are probably the origin of geomagnetism. What exactly drives the geodynamo is unknown, but the magnetic field is known to have existed for over 3000 My, with about the same strength as it has today, so the power supply must have been long-lasting. Magnetic fields in neutron stars are not believed to be of a dynamical origin within the neutron star itself[18] (see however refs 17 and 39) but there is the possibility to set up a Faraday type dynamo at the surface of the neutron star. We have considered elsewhere the details of the current flow through the magnetosphere[21] and have been able to show now[40] that the anomalous braking index of the Crab nebula pulsar (the explanation of which has presented a mayor difficulty for any theory developed so far) can be accounted for quantitatively in this model lending some support to its basic correctness. All we need to know here about the model are the following assumptions. The neutron star is slowed-down[1,2,21] or accelerated[3,4] by a magnetic torque provided by a current which flows along the magnetic field lines away from the surface area ΔF centred on the magnetic poles (polar caps). Forward- and return-current are spatially separated. In the simplest case the return-current will flow symmetrically about the forward-current and further away from the center of the polar caps (Fig. 1). No Hall-field can be established for geometrical reasons so the current $\vec{j}$ must spiral inwards in order to satisfy $\mathrm{div}\vec{j} = 0$. The ratio of the toroidal and the transverse current across the cap is

$$N = \frac{\Delta\phi}{\Delta p} = \frac{eB}{mc}\,\tau_e = \frac{\sigma B}{e n_e c} \qquad (2)$$

Here τ_e is the scattering time of an electron of the current with an ion in the crust. We shall assume that a fossil magnetic field of at least $10^{9,5}$ Gauss is present. Such a field is well below tha smallest yet observed pulsar field (which is $10^{10,3}$ Gauss for PSR 1913 + 16) in agreement with the prediction that pulsars with field-strengths below 10^{10} Gauss will not function as pulsars[41] and yet strong enough to force matter to form a "polymer" (quasi one -dimensional) metal[42,43] with density $\rho \approx 10^4$ gcm^{-3} corresponding to an electron density $n_e \approx 10^{27}$cm^{-3} at the surface. Where and how will the current flow? From Maxwell's equations we obtain with $\vec{j} = \sigma\vec{E}$ (dropping a small term) the diffusion equation for the electric field (and thereby also for the current)

$$\text{rot rot } \vec{E} = - \frac{4\pi\sigma}{c^2} \frac{\partial}{\partial t} \vec{E}$$

with the boundary consition at the polar cap that the tangential component of E be continuous ane equal to $-\nabla\phi$ where ϕ is the potential different across the polar cap which drives a current and which is probably due to a net charge on the pulsar[21]. The problem is the inverse to that of Ohmic dissipation[44] with the result that the current grows on the time-scale (see equ. (1)

$$\tau_g = \frac{2\sigma\Delta F}{c^2} \tag{3}$$

therefore we may safely take after some years $\sigma > 10^{20} s^{-1}$ and $\sigma/n_e > 10^{-7} cm^3 S^{-1}$. From equ. (2) we get then $N > 10^4 B_{12}$ (where B_{12} means B in units of 10^{12} Gauss). The transverse polar current, which breaks the pulsar's rotation or speeds the pulsar up in case of accretion can be inferred from observation (for known poloidal magnetic field-strenght) so that we can both compute the torroidal component of the current by means of equ.(2) and the magnetic field generated by it. Putting $\Delta F = \Pi R^2 \Theta^2$ where for pulsars typically[41] $\Theta \approx 10^{-1,5}$ and using for the torque T the re lation[17]

$$T = I\dot{\Omega} \approx -B_p \, B_t \, R^3 \Theta^3 \qquad (4)$$

we obtain for the dynamo field

$$\delta\vec{B}_p \approx \frac{\sigma I \dot{\Omega} \, \vec{B}_p}{e \, n_e c \, R^3 \Theta^3 \, |B_p|} \qquad (5)$$

Here I is the moment of inertia of the neutron star $(I \approx 10^{45} \mathrm{gcm}^2)$, and Ω the spin angular velocity of the pulsar. The index p means poloidal the index t toroidal. As a consequence of Lenz's rule δB_p is directed oppositely to the primordial magnetic field if the pulsar is slowed-down under the action of the self-generated current (anti-dynamo) and it is parallel to B_p (dynamo) if the pulsar is accelerated by the current due to accretion.

Under terrestrial conditions $N \ll 1$. For copper (very pure crystals)[45] at 4^0 K it is possible to achieve $\tau_e = 10^{-9}$ sec so that even with a 100 k Gauss field $N = 0{,}1$, too small to give rise to an interesting dynamo. For ordinary copper however[45] $\tau_e \approx 10^{-14}$ sec so that with the same magnetic field $N \approx 10^{-6}$, which is hard to measure. For neutron stars however the effect is very large, and we may accept for a moment the hypothesis that radio pulsars turn-off (as they cool below a certain temperature) and that Röntgen pulsars show pulsed emission (if they accrete enough) due to the dynamo mechanism, equ. (5) and see what this implies. If the conductivity is mainly due to electron-phonon scattering[12] we have $\sigma \approx 10^{20} \, T_6^{-5}$ i.e. the conductivuty is extremely temperature dependent. In the case of radio pulsars it is convenient to turn around equ. (5) and solve for the temperature. We obtain for pulsars near the cut-off line[46, 23] (which show nulling and which we identify tentatively with pulsars which are about to turn-off) with $\dot{\Omega} \approx -10^{-16}\,S^{-2}$, $\Theta \approx 10^{-1}$, $B_p \approx \delta B_p \approx 10^{12}$ Gauss a temperature $T \approx 10^{4,7}\ {}^0K$, a temperature that a pulsar could easily sustain with the help of a little reheating (due to the return current[22]). For Röntgen pulsars we may on the other hand put $T \approx 10^{7}\ {}^0K$ for the surface temperature and $\Theta \approx 10^{-1,5}$ to obtain $\delta B_p \approx 10^{12}$ Gauss in good agreement with the observations if we use[47, 4] $\dot{\Omega} \approx 10^{-12}\,S^{-2}$ as inferred from the speed-up.

Having established the relevance of the unipolar dynamo mechanism for pulsar evolution it seems worthwhile to examine the observational evidence with more scrutins and this will be done in a forthcoming paper. One interesting prediction of the present model would be that due to the extreme temperature dependence of the dynamo effect pulsars could suddenly turn on for a short period due to a sudden heating[32] and it would be interesting to know, whether such events have already been observed but not recorded in publishing form. To this end observers at independent observatories could check through their data together (as is e.g. done with the x-ray data).

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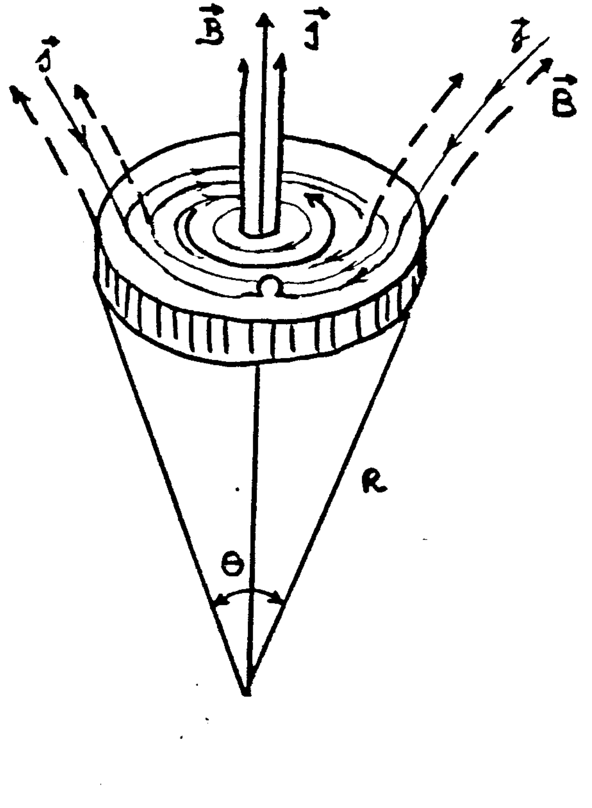
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