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# On the Nature of Magnetars

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**Abstract.** The electromagnetic fields of magnetodipole radiation can penetrate to the conducting matter of a neutron star crust and create there electric currents and tangential magnetic fields of high magnitude. The solution obtained here has the form of surface magnetic field discontinuities propagating through the crust to the core. This model explains the phenomena of magnetars — Soft Gamma-ray Repeaters and Anomalous X-ray Pulsars.

## 1. Introduction

The main idea lying at the base of pulsar physics is that of magnetodipole radiation. For many years after the discovery of radio pulsars in 1967, physicists believed that neutron star activity is due to the rotating strong magnetic field frozen into the star's interior. A rotating magnetic dipole of moment $M$ produces so called magnetodipole radiation, i.e., electromagnetic waves of frequency $\Omega$ equal to the body rotation frequency. The full solution for magnetodipole radiation is based on the solution of electrodynamic equations inside the neutron star and outside, in a vacuum. This is known as the Deutsch (1955) solution and was obtained for any magnetized star. From this solution it follows that three components of electromagnetic field, $B_\theta$, $B_\phi$, $E_r$ are discontinuous on the star surface $r = R$. As a consequence, the surface current $\mathbf{J}_S$ and surface charge $Q_S$ appear. The surface currents play an important role in the dynamics. They transform the mechanical angular momentum and energy of the body to the angular momentum of the electromagnetic field and its energy flux.

## 2. Diffusion of the Current

What will happen if we have not an ideal body (star) but have finite, even large conductivity $\sigma$? First of all, the surface currents $\mathbf{J}_S$ wants to spread into the volume because the conductivity $\sigma$ is proportional to the density $\rho$ of the neutron star matter, $\sigma \propto \rho^{2/3}$ (Blandford, Applegate, & Hernquist 1983) and grows with depth $h$. Moreover, the radiation field pushes the surface current inside. This means that the discontinuity of the tangential components of magnetic field will spread into the volume. This is described by the magnetic field diffusion equation following from the Maxwell equations inside the rotating body, $\partial B_t/\partial t = \partial/\partial h \eta \partial B_t/\partial h$. The coefficient of magnetic diffusion $\eta = c^2/4\pi\sigma$ depends strongly on the depth $h$ ($h \propto \rho^{1/3}; \eta \propto \rho^{-2/3} \Longrightarrow \eta \propto h^{-2}$):



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the higher the depth, the smaller the diffusion. Such dependence of $\eta$ on the coordinate leads to the formation of a shock front, propagating with positive velocity $U = -\partial\eta/\partial h$. The discontinuities of the tangential components of magnetic field $B_\theta, B_\phi$ propagate inside! This means that the vacuum fields of the electrical quadrupole radiation penetrate to the body of finite conductivity growing with depth. Quadrupole radiation brings with itself also the electric field of quadrupole character, exciting the electric currents. In other words, the young neutron star, rotating and magnetized, can have two paths for its evolution. The first one is known as a radio pulsar. If it can create a magnetosphere filled by plasma with high conductivity greater than the conductivity of the surface layers of the neutron star, then the surface currents will move through the magnetosphere to the light cylinder surface pushing out the magnetodipole radiation and originate the corotating magnetosphere with Goldriech-Julian charge density. The activity will be only in the polar region where the plasma along the open magnetic field lines escapes to the outside (see, for example, Beskin, Gurevich, & Istomin 1993). But if a neutron star is born with a large period of rotation $P$ and small magnetic moment $M$ or large surface magnetic field $B_0$, the efficiency for creating a magnetospheric plasma with large-enough density is small and the star seems to radiate magnetodipole radiation. However, the Deutsch solution takes place only in the case of infinite conductivity $\sigma = \infty$ or $\eta \equiv 0$. At small finite magnetic diffusion $\eta$, the electric field of the radiation begins to penetrate into the neutron star interior inducing electric currents and heating. It is well known that the electric fields induced by changing magnetic fields penetrating inside the conducting material produce so-called eddy currents resulting in catastrophic consequences. To prevent this phenomenon, the metallic parts of electric machines are cut over well-isolated thin layers making the effective conductivity $\sigma_{\text{eff}} \to 0$. But in the case of a neutron star nobody implemented this procedure, and it has to follow another path. In the literature, this population is known as magnetars, consisting of two groups — Anomalous X-ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs).

The tangential magnetic field $B_c$, generated by the electric currents in the crust, is $10^{14-15}$ gauss, and the magnetic energy released is $W_B \approx 10^{35}\,\text{ergs}\,\text{s}^{-1}$. The depth of the penetration depends on time, $h = 12(t/1\,\text{yr})^{1/4}$ meters. For time $t \simeq 10^3$ yr, as for the SGRs, $h \simeq 70$ m. In this thin layer the currents create the stresses that can crack the crust if $h < 100$ m. This will be observed as an SGR gamma-ray burst. For deeper penetration the cracking of the crust is not so probable and it becomes possible for a continuous release of the energy of the magnetic field $B_c$. This is an AXP.

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## References

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