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Laboratory Modelling of Neutron Star Magnetospheres

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Abstract

The problem of modelling a rotating neutron star magnetosphere is discussed. Attention is drawn to the possibility of qualitative modelling of this cosmic object without conforming to the similarity laws. Two models, one simulating an aligned magnetic rotator and the other an oblique rotator, are suggested. Preliminary results from such modelling of pulsar magnetospheres in the oblique rotator case are reported.

Introduction

At present, difficulties in creating a theory of pulsar radiation are associated to a great extent with our lack of a reliable model for a neutron star magnetosphere. The important ideas of Goldreich and Julian (1969) on the corotating magnetosphere surrounding a spinning neutron star, of Sturrock (1971) and of Ruderman and Sutherland (1975) on the creation of electron–positron pairs filling the magnetic shell of a pulsar, and the concepts of Radhakrishnan and Cooke (1969) and Smith (1969) on the localization of the radiation source in a neutron star magnetosphere all need further exploration. For we cannot yet judge with confidence a magnetosphere structure, the distribution and acceleration of particles in the magnetosphere, or localization of the radiation source.* We thus do not know which region of the magnetosphere yields the radiation observed at the Earth or by what it is physically specified. The mechanism of pulsar radio emission is also unknown.

From the above discussion it is clear that at present the central problem of the whole theory of pulsars is to construct a reliable model of the pulsar magnetosphere. Without it, further progress in our understanding of pulsar phenomena is impossible. While advance in this direction will depend mainly on the development of successful theory, it seems to us that special experimental investigations will also be useful, and in this paper we wish to draw attention to the possibility of the laboratory modelling of the magnetosphere of a rotating neutron star. We report here the preliminary results from such modelling.

* For instance, in the report on the 1974 Australian–American Symposium, Manchester (1974) noted Sturrock's model of the magnetosphere (see Roberts and Sturrock 1972, 1973), as the most advanced one. But this model is not correct, since it is based on the assumption that the particle distribution in the magnetosphere is defined by gravitational and centrifugal forces only; the influence of electric fields is ignored, for the electric field of a rotating star is compensated by the field of the space charge in the magnetosphere. However, it is just this compensation that determines the character of the particle distribution; weak gravitational and centrifugal forces make comparatively small corrections to the distribution (Ginzburg and Zheleznyakov 1975).

The general purpose of the pulsar modelling is to obtain information of:

(1) the charged particle distribution in the magnetosphere of a rotating neutron star and its peculiarities which can indicate localization of a radiation source;

(2) the particle velocity distribution, including the question of particle acceleration and corotation of plasma around the spinning star;

(3) compensation of the star electric field by the spatial particle charge in the magnetosphere and 'deformation' of the star magnetic field by electric currents in the magnetosphere.

The possibility of obtaining useful results by modelling plasma phenomena is mainly based upon the existence of so-called similarity laws (see Alfvén and Fälthammar 1963). These laws indicate the scaling of electrodynamic values between a cosmic object and a laboratory model. In accordance with one similarity law, the magnetic field B is inversely proportional to the linear scale L. This means that, in transforming a neutron star of 10^6 cm radius into a laboratory model of 10 cm dimension, it is necessary to increase the magnitude of the magnetic field (10^{12} G $\equiv 10^8$ T) by 10^5 times. Such modelling is obviously not feasible.

At first sight, the foregoing conclusion may seem most discouraging. However, this need not be so. The point is that usually the qualitative features of electromagnetic phenomena in a plasma are defined by two factors: (1) the magnetic field configuration and the form of the particle velocity distribution, and (2) the relative values of the dimensionless parameters inherent in the given phenomenon. When the parameters are sufficiently greater or smaller than unity, the qualitative character of particular processes is not sensitive to their accurate values. This circumstance enables one to depart from the similarity laws but still carry out a qualitative modelling of cosmic processes in a laboratory by preserving strong inequalities for typical dimensionless parameters (e.g. ω_B/ω_L, $\omega_B/\nu_{\text{eff}}$ etc., where ω_B is the gyrofrequency, ω_L the plasma frequency and ν_{eff} the effective collision frequency). The construction of a laboratory system with such inequalities is a simpler and more practicable problem. The choice of the dimensionless parameters depends on the specific cosmic phenomenon being considered and on the results derived from special analysis of the problem.

Neutron Star Models

The laboratory modelling of a pulsar magnetosphere may be realized within a vacuum chamber with linear dimension L up to 1 m. In the first place, it is necessary to simulate outside a sphere of about 10 cm radius (the 'star') electromagnetic fields with a configuration typical of that near a rotating neutron star. For the localization of the light cylinder of radius $r_c = c/\Omega$ in the vacuum chamber, the angular velocity Ω of the sphere rotation must exceed $2c/L \sim 6 \times 10^8\ \text{s}^{-1}$ (i.e. ~ 100 MHz). It is evident that mechanical rotation is not practicable here. A possible solution is to place inside the spherical volume a suitable stationary source which will produce outside the sphere an electromagnetic field identical with that of a rotating neutron star.

Unipolar Inductor. A neutron star with a rotation axis $\mathbf{\Omega}$ along its magnetic dipole $\boldsymbol{\mu}$ (aligned rotator) generates a quadrupole electric field in vacuum around the star. This field together with its dipole magnetic field is illustrated in Fig. 1*a*.

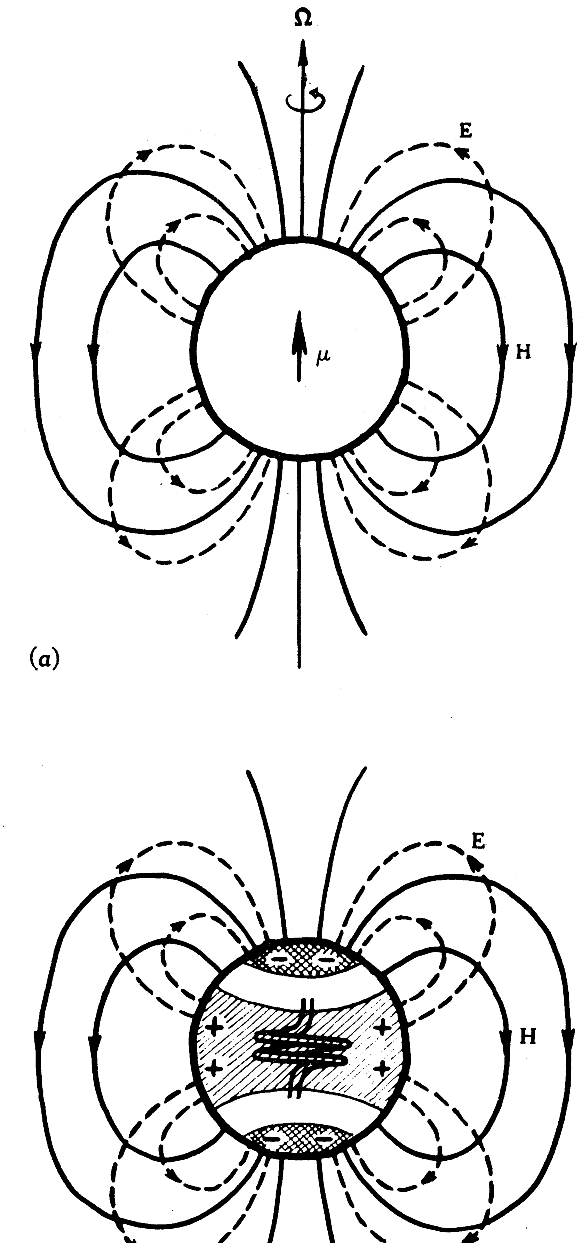

Fig. 1. Unipolar inductor: (*a*) electric and magnetic fields in vacuum around a neutron star with its rotation axis **Ω** along its magnetic dipole **μ** (aligned magnetic rotator); (*b*) modelling this configuration with a current-carrying coil inside a sphere.

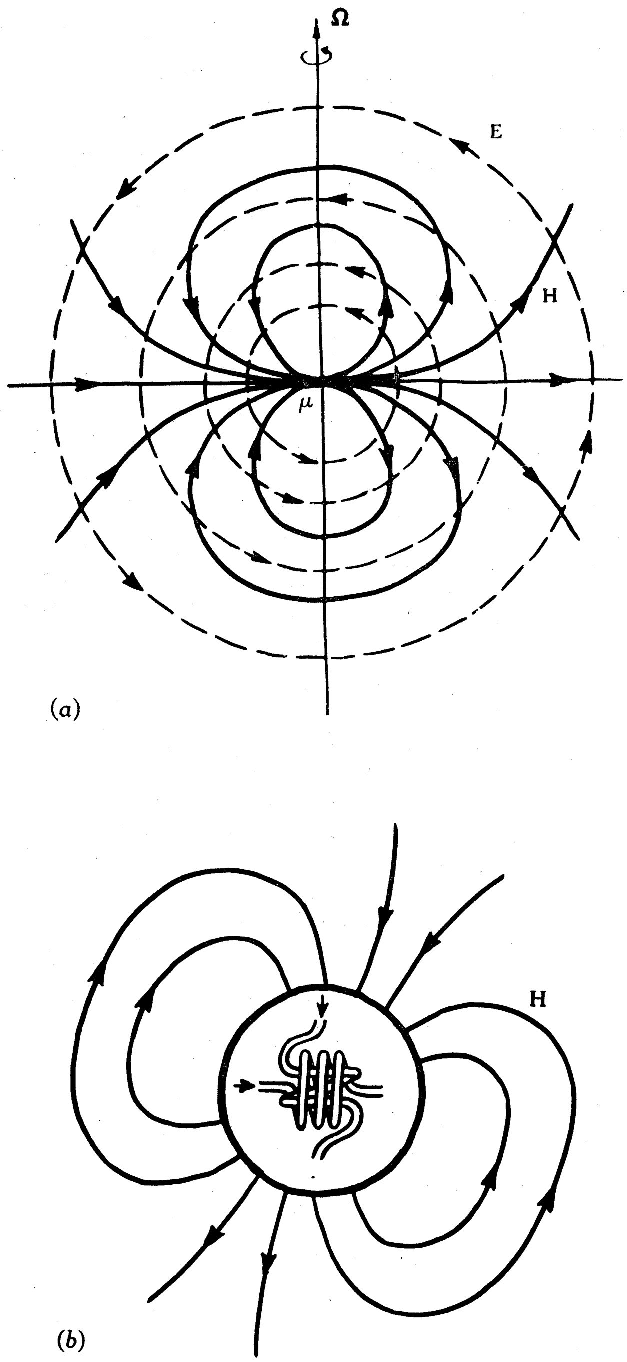

Fig. 2. Oblique magnetic rotator: (*a*) electric and magnetic fields in vacuum around a neutron star with its rotation axis **Ω** perpendicular to its magnetic dipole moment **μ**; (*b*) model of this configuration.

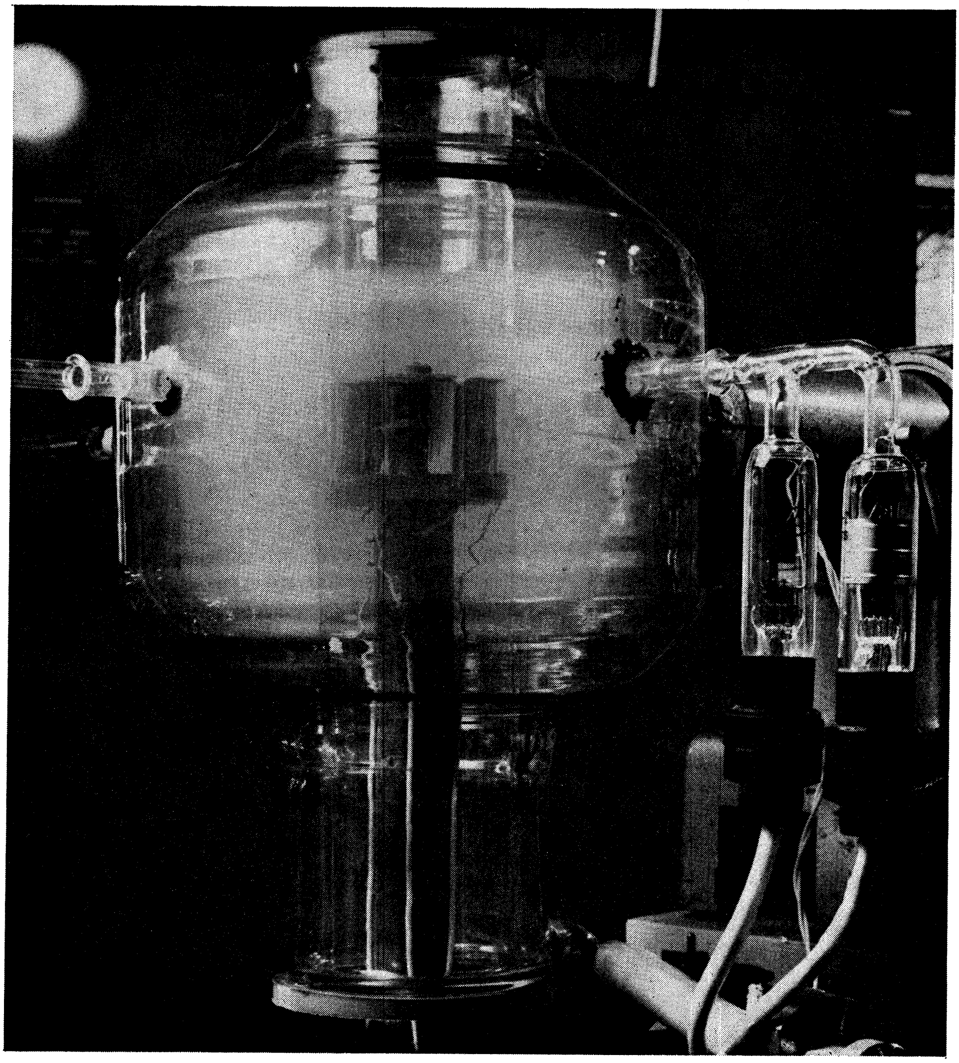

Fig. 3. Laboratory device (vacuum chamber and coils) for the modelling of plasma processes around an oblique magnetic rotator with $\boldsymbol{\mu} \perp \boldsymbol{\Omega}$.

When modelling such a unipolar inductor, the constant magnetic field may be created by a current-carrying coil placed inside the sphere; for a source of the electric field, the quadrupole configuration presented in Fig. 1*b* may be employed. The equivalent angular velocity Ω_{eq} in the model of a unipolar inductor with infinite conductivity is defined by the relation

$$\Omega_{eq} = cU_0/B_0 R_0^2, \tag{1}$$

where U_0 is the voltage applied between the pole and equator, B_0 is the magnetic field at the equator and R_0 is the sphere radius.

Oblique Magnetic Rotator. Modelling a rotating neutron star with $\boldsymbol{\mu}$ not parallel to $\boldsymbol{\Omega}$ is simpler in the case where the magnetic dipole moment is orthogonal to the rotation axis ($\boldsymbol{\mu} \perp \boldsymbol{\Omega}$). In this variant, there is no component of the magnetic moment along the rotation axis and the quadrupole electric field is also absent. In a vacuum outside the star, there exists only the rotating magnetic field $\boldsymbol{B}$ and the circuital electric field $\boldsymbol{E}$ related to it. At every point the vector $\boldsymbol{E}$ is parallel to the plane in which $\boldsymbol{\mu}$ and $\boldsymbol{\Omega}$ are located. Then the electric field lines are circles, and their centres coincide with the star centre or are displaced in a direction perpendicular to the magnetic moment $\boldsymbol{\mu}$ and the angular velocity $\boldsymbol{\Omega}$ (Fig. 2*a*). Electric and magnetic fields like those of a rotating magnetic dipole may be formed by a system of two coils with orthogonal axes, if their currents are alternating with frequency Ω and phase difference $\frac{1}{2}\pi$. These coils are located inside the sphere in the way shown in Fig. 2*b*.

As a source of plasma in the two models considered, neutral gas surrounding the spherical 'star' may be employed. The plasma will be formed due to electrical discharge in the constant electric field of the aligned rotator model (unipolar inductor), or due to a high frequency discharge in the oblique rotator model. Such a method of 'magnetosphere' formation would seem to be similar to the gas accretion on a neutron star.

First Experiments

In our preliminary model experiment, the oblique magnetic rotator with $\boldsymbol{\mu} \perp \boldsymbol{\Omega}$ was simulated in the device shown in Fig. 3. The vacuum chamber of toroidal type is formed between surfaces of two coaxial glass cylinders with closed butt ends. The external diameter is 30 cm and the internal diameter 10 cm. The gas density in this chamber falls to 10^{14}–10^{15} particles cm^{-3} (i.e. 10^4–10^5 times less than under normal atmospheric conditions). The composition is a mixture of air and argon. Two orthogonal coils are placed in the internal cylinder at normal gas pressure. These coils are fed by two generators. Their power is about 2 kW in the pulsed mode (pulse duration is 10^{-3} s); the frequency Ω is equal to 1 MHz. The generators, which are synchronized with a constant phase shift of $\frac{1}{2}\pi$, provide a rotating magnetic field in the vacuum chamber; the field intensity is 2 G near the external cylinder and about 50 G near the internal one.

In the chamber there is also a hot cathode. It yields initial electrons to produce the high frequency discharge and ionization of the neutral gas by the circuital electric field. The degree of ionization is about 10^{-2}–10^{-3}; electron energy is about 5 eV. The gas discharge is seen in Fig. 3.

At the initial stage of these experiments the major purpose is to detect plasma corotation (i.e. to obtain data on the participation of magnetospheric plasma in the rotation of a magnetized neutron star). Theoretical analysis of this problem has not yet given definite results, and we hope that model experiments will be rather useful.

From a microscopic point of view, the orbital component of velocity (in the direction $\boldsymbol{u} = \boldsymbol{\Omega} \times \boldsymbol{r}$) is related to the drift of the charged particles in crossed electric and magnetic fields. The drift conditions in the pulsar magnetosphere, namely

$$\nu_{\mathrm{eff}}/\omega_B \ll 1\,, \qquad \Omega/\omega_B \ll 1\,, \qquad u/\omega_B r \ll 1\,, \tag{2a, b, c}$$

are satisfied to a great extent. They must be also satisfied within the modelling device. The first inequality (2a) permits an electron to make many orbits in the magnetic field between any two collisions with other particles. The inequality (2b) means that the rotation period of an electron in the magnetic field is much less than the period of field alternation. The inequality (2c) requires the gyroradius to be small compared with the scale of the magnetic field inhomogeneity (this scale is of the order of the particle distance r from the inductor's centre). Such conditions must exist for ions also:

$$\nu_{\mathrm{eff,i}}/\omega_{B,\mathrm{i}} \ll 1\,, \qquad \Omega/\omega_{B,\mathrm{i}} \ll 1\,, \qquad u_{\mathrm{i}}/\omega_{B,\mathrm{i}}\, r \ll 1\,. \tag{3a, b, c}$$

However, the drift conditions for ions are satisfied with greater difficulty than those for electrons due to their greater mass.

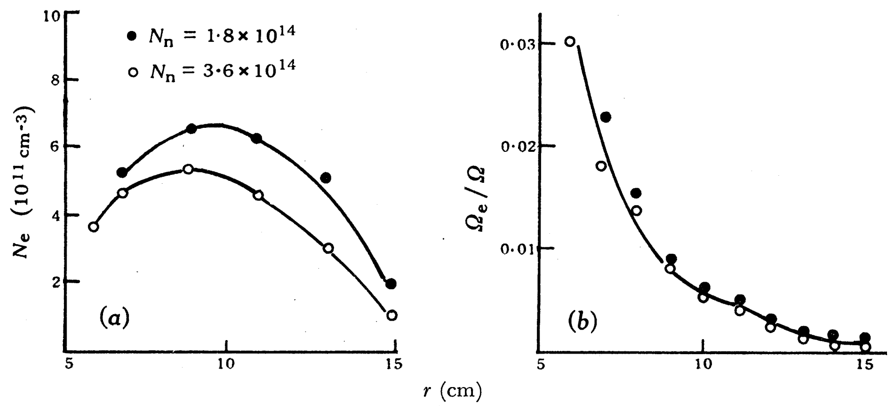

Fig. 4. Modelling results for the radial distribution of (*a*) the electron density N_e and (*b*) the orbital electron angular velocity Ω_e. In each case the results are shown for neutral gas densities N_n of $1 \cdot 8 \times 10^{14}$ and $3 \cdot 6 \times 10^{14}\ \mathrm{cm}^{-3}$.

Let the light cylinder be located inside the vacuum chamber with linear size L (a desirable situation), that is, $r_c = c/\Omega < L$. For our case $L = 30$ cm and hence we must have the frequency $\Omega > 10^9\ \mathrm{s}^{-1}$. It is concluded that the inequality (2b) above will be valid if the condition

$$\omega_B \gg c/L \tag{4}$$

is achieved.

In our device the condition (4) can be satisfied only for strong magnetic fields: $B \gg 10^2$ G for electrons and $B \gg 10^5$ G for ions. Such fields at frequencies $\Omega > 10^9\ \mathrm{s}^{-1}$ are difficult to realize and we have taken an Ω value that is about two orders of magnitude less (1 MHz). Then unfortunately the light radius extends far beyond our model system and, as a result, we can only model the pulsar magnetosphere in the near (quasi-stationary) zone. However, this smaller value of Ω does satisfy the drift conditions for electrons at weaker magnetic fields (of the order of some tens of gauss). Thus in our experiment the drift conditions are fulfilled for electrons in the inner part of the vacuum chamber but they are broken for ions everywhere.

Preliminary results from these early experiments are as follows.

The first result is presented in Fig. 4*a*. This plot shows the dependence of the electron density N_e on the distance r to the centre of the coils (the centre of a 'star').

One could expect a steady decrease in the electron density towards the periphery of the vacuum chamber because of the decrease in the ionizing electric field intensity. However, this does not occur. In the inner part of the chamber near the coils (the 'star') there is a region of lower density, and it is only beyond a certain distance from the coils that the density decreases steadily towards the external cylinder. This result gives the impression that the combination of rotating electric and magnetic fields 'sweeps out' the electrons from the central region of a strong field. (This effect was not realized for nonrotating fields, i.e. for the case where the electric currents in both coils had the same phase.) In our experiment, the 'sweeping out' process terminates at the periphery. In this region the drift approximation also breaks down. This result would seem to be of interest for the theory of a pulsar magnetosphere.

The second result is related to plasma corotation due to spinning fields. An orbital component Ω_e of the electron motion around the 'star' has been recorded in our experiments. However, according to Fig. 4*b*, the angular velocity of the electron component does not coincide with the angular frequency Ω of the magnetic field, and it is substantially smaller than the latter. Presently, we are not sure of the absolute values of the recorded orbital velocities, and this aspect needs further testing. An orbital motion of ions has also been observed, though relatively slower than that of the electrons.

The above results give the electron density and electron velocity values averaged over the field rotation period. More detailed information of the particle distribution and motion is not yet available. In future experiments, we hope to investigate more thoroughly the rotating plasma in our device and also to model the other system, namely an aligned rotator or unipolar inductor.

It should be noted that experiments on plasma motion in rotating electromagnetic fields have been carried out previously (see e.g. the review by Lehnert 1971). The experiments closest to our work are the investigations by Blevin and Thonemann (1962) and Averin *et al.* (1978). However, the configuration of the rotating magnetic field used in these experiments was different: it resembled the field produced by the stator of an AC electromotor, and the cylindrical plasma column played the part of a rotor. The purpose and conditions of the experiments also differed from ours.

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