Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 56 (2015) 964–969

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

An analysis of magnetic field and magnetosphere of neutron star under effect of a shock wave

S.I. Bezrodnykh [a,b,*], B.V. Somov [a]

[a] Sternberg Astronomical Institute, Lomonosov Moscow State University, 119991, Universitetskii prosp 13, Moscow, Russia

[b] Dorodnicyn Computing Centre of the RAS, 119333, Vavilova str. 40, Moscow, Russia

Received 28 December 2014; received in revised form 6 April 2015; accepted 20 May 2015
Available online 28 May 2015

Abstract

We consider a model of magnetosphere of a neutron star subjected to a strong shock wave from supernova explosion. In this model a form of magnetosphere's boundary is determined from the condition of equilibrium between external gas pressure behind the shock and interior magnetic pressure. The field of neutron star is approximated as a point magnetic dipole. The magnetic field is assumed to be potential in circumstellar space. In magnetotail there is a reconnecting current layer, which accumulates an excess magnetic energy. The model under consideration is reduced to consequent solution of two Riemann–Hilbert problems. The obtained analytic solution of the both problems, in particular, shows the presence of reverse current in the current layer. The solution has importance for possibility estimation of directional relativistic plasma jets and impulse bursts of gamma-impulses or hard radiation of other kinds.

Keywords: Neutron stars; Supernova; Magnetosphere; Magnetic reconnection

1. Introduction

In physics of neutron stars and cosmic gamma-ray bursts (Heyvaerts and Priest, 1989; Paczynski, 2001; Granot and Loeb, 2003; Cheng and Romero, 2004; Lyutikov, 2006; Becker, 2009; Colpi et al., 2009) a fundamental problem consists in calculation magnetosphere's shape and magnetic field inside a magnetosphere during the passage of a strong shock wave from supernova explosion. We assume that, having a huge energy, the shock rapidly compresses and deforms the magnetic field. The shock front presumably grabs and entrains part of the field, creating an elongated magnetospheric tail in the direction of the shock propagation (Somov, 2011a,b). Mechanical energy of a shock is converted into magnetic energy of current layers, that are subjected to unbalanced magnetic forces. The boundary of such essentially unbalanced magnetosphere is determined by the equality of gas pressure p of the incident plasma flux and pressure $\mathbf{B}^2/8\pi$ of the magnetic field filling the circumstellar space.

We also assume that the magnetic force $\mathbf{B} \times \mathrm{rot}\,\mathbf{B}$ dominates over the gas pressure gradient, gravitational, and other forces up to appreciable distances from the star to the magnetosphere's boundary. In this connection, a strong field approximation (Somov, 2013) can be applied to describe the magnetohydrodynamic processes in the magnetosphere. Relaxation of the excess magnetic energy proceeds by the mechanism of fast magnetic reconnection, which is known as most efficient means of transforming magnetic-field energy into particle energy (Priest and Forbes, 2000; Larrabee et al., 2003; Hurley et al., 2005; Benz and Güdel, 2010; Somov, 2013). The given physical

* Corresponding author at: Sternberg Astronomical Institute, Lomonosov Moscow State University, 119991, Universitetskii prosp 13, Moscow, Russia.

E-mail addresses: sbezrodnykh@mail.ru (S.I. Bezrodnykh), somov@sai.msu.ru (B.V. Somov).

http://dx.doi.org/10.1016/j.asr.2015.05.032
0273-1177/

reasoning imply statement of the problem of finding the shape of magnetosphere's boundary and calculating magnetic field filling the circumstellar space. Its solution will give an opportunity to estimate possible directional relativistic plasma jets and impulse bursts of hard electromagnetic radiation.

In this work we consider the model of magnetosphere proposed in Somov (2011a,b). This model supposes that the stellar magnetic field is approximated by a point dipole and a plane neutral current layer is located in the magnetospheric tail. More exactly, we assume that a powerful shock strongly deforms the stellar magnetic field, generating a system of electric currents. They are closed mainly along the pathes of smallest length and consequently the lowest inductance. In the frame of our simplified model, we do not know these pathes but for us it is important the following. The electric currents in the region where antiparallel field components emerge can be closed not on the remote boundary but locally, in the region of a reverse current, usually interpreted as a manifestation of the plasma flow inertia at the stage of current layer formation. The force **F** acts on the edge of the reverse current and tends to eliminate the reverse current (Fig. 1(a)).

The shape of magnetosphere is defined by the above mentioned condition $\mathbf{B}^2/8\pi = p$, where magnetic field **B** is considered to be potential. The problems like this allowing for free boundaries have been studied in astrophysics by many researchers for a long time, see e.g. (Chapman et al., 1931; Alfvén, 1950; Zhigulev, 1959; Zhigulev and Romishevskii, 1959; Unti et al., 1968; Oberts, 1973). However, no solutions have been obtained in a closed

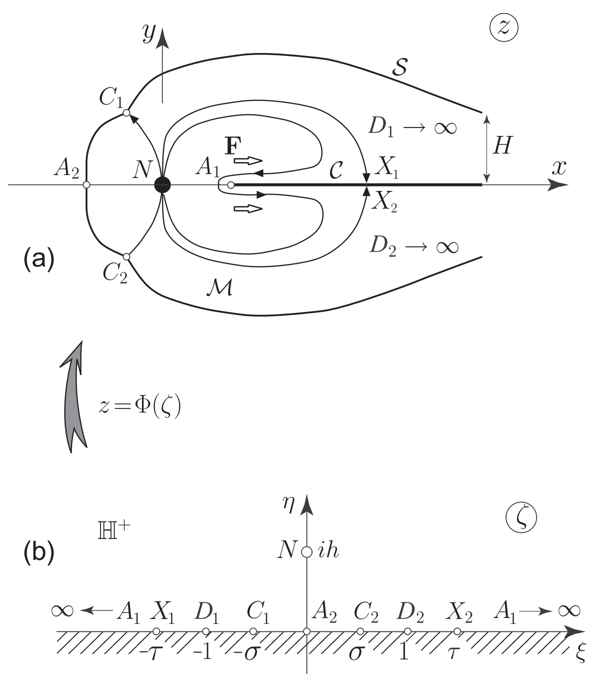

Fig. 1. Scheme for the solution to the problem of finding shape of the magnetospheric boundary and the magnetic field.

analytical form for models with current layers. The results of our work were delivered at COSPAR-2014 (Bezrodnykh and Somov, 2014).

2. Statement of the problem on calculation of magnetosphere's shape and magnetic field

In the considering model, the magnetosphere of a neutron star, schematically depicted at Fig. 1(a), is a symmetric simply connected domain $\mathcal{M}$ in the complex plane $z = x + iy$. A point magnetic dipole modeling the stellar field is located at the origin of coordinates $z = 0$, which is denoted by N. The dipole with value μ is directed along the y axis. The boundary of domain $\mathcal{M}$ is composed of two arcs, $\mathcal{S}$ and $\mathcal{C}$. The shape of curve $\mathcal{S}$ that represents the magnetopause is not known a priori. The infinite rectilinear cut $\mathcal{C}$ along the real axis is a cross section of the current layer perpendicular to z-plane.

The planar magnetic field $\mathbf{B} = \big(B_x(x,y), B_y(x,y), 0\big)$ is assumed to be potential in domain $\mathcal{M}$ except for the origin N. For its analysis, it is convenient to introduce "complex" magnetic field

$$\mathcal{B}(z) = B_x(x,y) + iB_y(x,y)$$

because the conjugated function $\overline{\mathcal{B}}(z)$ is an analytic one in $\mathcal{M} \setminus \{0\}$. Near point $z = 0$ the following asymptotic relationship holds:

$$\overline{\mathcal{B}}(z) = i\,\frac{\mu}{z^2} + \mathcal{O}(1), \quad z \to 0. \tag{1}$$

The magnetopause $\mathcal{S}$ is defined by an equality between the external gas pressure p of the plasma flux and the magnetic field pressure $\mathcal{B}$:

$$\frac{|\mathcal{B}|^2}{8\pi} = p, \quad z \in \mathcal{S}; \tag{2}$$

where p is assumed to be constant and is a parameter of the model. It is assumed that the magnetic field does not penetrate $\mathcal{S}$ and $\mathcal{C}$: i.e., the following relationships are valid:

$$(\mathbf{B}, \mathbf{n}) = 0, \quad z \in (\mathcal{S} \cup \mathcal{C}), \tag{3}$$

where $\mathbf{n}$ is a vector normal to $\mathcal{S}$ or $\mathcal{C}$. The coordinate $z = \varepsilon$ of the end point A_1 and the halfwidth H of the magnetospheric tail at infinity are prescribed.

To describe the field $\mathcal{B}(z)$ we introduce a complex potential, which is an analytical function $\mathcal{F}(z)$ related to $\mathcal{B}(z)$ by the relationship

$$i\,\mathcal{F}'(z) = \overline{\mathcal{B}}(z). \tag{4}$$

Potential $\mathcal{F}(z)$ is assumed to be continuous in $\overline{\mathcal{M}} \setminus \{N, D_1, D_2\}$.

Condition (3) and this continuity imply that the real part of $\mathcal{F}(z)$ takes constant values, which are assumed to be equal to 0 and $-\pi Q$, respectively, at the $\mathcal{S}$ and $\mathcal{C}$ arcs of the domain $\mathcal{M}$ boundary.

Relationships (1) and (3) yield the following conditions for the potential: