Axially symmetric electromagnetic structures in astrophysics and nature of relativistic jets. .

Yuri A. Rylov

Institute for Problems in Mechanics, Russian Academy of Sciences,
101-1, Vernadskii Ave., Moscow, 117526, Russia

Abstract

Concepts of gravitational and electromagnetic structures of astrophysical objects are introduced. The two structures have different properties and stationary states. In some cases the electromagnetic structure appears to be dominating. Relativistic jet is a typical attribute of electromagnetic structure. In particular, high degree of the jet collimation is explained freely as a phenomenon of the electromagnetic structure, and hardly can be explained in terms of magnetohydrodynamics. Interaction between the gravitational and electromegnetic structures is considered and estimated.

1 Introduction

Last decade one observes and intensively investigates astrophysical objects, known as relativistic jets [3, 12]. In many cases these jets are interpreted as two-sided moving beams of relativistic particles. Origin of acceleration of such powerful well collimated flows of relativistic partilces is uncleair now. Attempts to explain them as a result of some MHD mechanizm [2, 9] met difficulties, because it is hard to explain strong collimation of jets [19, 10, 1]. In general, magnetohydrodynamics describes such flows of conducting fluid, where longitudinal (to magnetic field) component of the electric field is very small. In such a situation an acceleration of charged particles and their collimation is hardly possible. But there are such flows of a gas, consisting of charged particles, when in some region the longitudanal component of the electric field cannot be compensated, because the whole electromagnetic structure of the object does not admit this.

An example of such an object is rapidly rotating magnetic neutron star (pulsar) with the aligned magnetic moment. For such a neutron star the two-sided relativistic electron-positron jets along the magnetic axis are reasonable elements of the total electromagnetic structure [18]. It is very important that this result can be obtained only at global consideration of the neutron star and its environment. Local consideration of electromagnetic processes does not enable to derive the well collimated relativistic jets.

It is very interesting that electromagnetic structure appears to be important also in the case, when it is usually neglected. Let us consider upper atmosphere of a star with parameters of the Sun: the mass $M = 2 \cdot 10^{33}$g, the period of revolution $P = 3 \times 10^6$s and radius $R = 7. \times 10^{10}$cm. The star is supposed to have magnetic field, axially symmetric with respect to the rotational axis. On the surface of the conducting star appears the surface electric charge which together with the space stellar charge generates an electric field around the star [4]. Let the characteristic magnetic field on the stellar surface be $H = 1$gs, then the electric field E is of the order βH, where $\beta = \Omega R/c$, $\Omega = 2\pi/P$.

Motion of the completely ionized gas, consisting of protons and electrons, in vicinity of the star is described in the collisionless approximation by dynamic equations

$$\nabla \mathbf{H} = 0, \qquad \frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{c}\nabla \times \mathbf{E}, \qquad \nabla \mathbf{E} = 4\pi e\,(n_+ - n_-) \tag{1}$$

$$\nabla \times \mathbf{H} = \frac{4\pi e}{c}\,(n_+ \mathbf{v}_+ - n_- \mathbf{v}_-) + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} \tag{2}$$

$$\frac{\partial n_\pm}{\partial t} + (\nabla, n_\pm \mathbf{v}_\pm) = 0 \tag{3}$$

$$m_\pm n_\pm \left(\frac{\partial}{\partial t} + (\mathbf{v}_\pm, \nabla)\right) \gamma_\pm \mathbf{v}_\pm + \nabla p_\pm = n_\pm \mathbf{F}_\pm, \qquad \gamma_\pm = \left(1 - \frac{\mathbf{v}_\pm^2}{c^2}\right)^{-1/2} \tag{4}$$

$$\mathbf{F}_\pm = m_\pm \mathbf{g} \pm e\left(\mathbf{E} = \frac{\mathbf{v}_\pm}{c} \times \mathbf{H}\right), \qquad p_\pm = kT_\pm n_\pm, \tag{5}$$

where $m_\pm, n_\pm, \mathbf{v}_\pm, T_\pm$ are respectively the mass, concentration, velocity and temperature. Index $(+)$ associates with proton an index $(-)$ does with electron.

Let us reduce dynamic equations (4) to a dimensionless form, using the quantities $R^* = 7.0 \times 10^{10}$cm, $M^* = 2.0 \times 10^{33}$g, $H^* = 1$Gs, $\Omega = 3.0 \times 10^{-6}\mathrm{s}^{-1}$, $T^* = 6. \times 10^3$K as scale parameters. $g = 2.7 \times 10^4 \mathrm{cm} \times \mathrm{s}^{-2}$ and $c = 3. \times 10^{10}$cm are respectively the gravitational acceleration on the stellar surface and the speed of the light.

Let us introduce dimensionless variables

$$\xi = \mathbf{x}/R^*, \qquad \tau = \Omega t, \qquad w = \frac{v}{\Omega R^*}, \qquad \beta = \frac{\Omega R^*}{c}, \qquad \nabla' = R^* \nabla = \frac{\partial}{\partial \xi}$$

$$\mathbf{h} = \frac{\mathbf{H}}{H^*}, \qquad \mathbf{e} = \frac{\mathbf{E}}{H^*}, \qquad t_\pm = \frac{T_\pm}{T^*}, \qquad \beta = \frac{\Omega R^*}{c} = 7.0 \times 10^{-6}$$

Then the equations (4) take the form

$$\begin{aligned} & a_D n_+ \left(\frac{\partial}{\partial \tau} + (\mathbf{w}_+, \nabla')\right) \gamma_+ \mathbf{w}_+ + a_T \nabla' (t_+ n_+) \\ = \quad & n_+ m_p \frac{\mathbf{g}}{e\beta} + n_+ \left(\frac{\mathbf{e}}{\beta} + \mathbf{w}_+ \times \mathbf{h}\right) \end{aligned} \tag{6}$$

$$
\begin{aligned}
& a_d n_- \left(\frac{\partial}{\partial \tau} + (\mathbf{w}_-, \nabla') \right) \gamma_- \mathbf{w}_- + a_T \nabla' (t_- n_-) \\
= \; & n_- m_e \frac{\mathbf{g}}{e\beta} \pm n_- \left(\frac{\mathbf{e}}{\beta} + \mathbf{w}_- \times \mathbf{h} \right)
\end{aligned} \tag{7}
$$

where dimensionless coefficients a have the form

$$
a_D = \frac{m_p c^2}{eH^* R^*} \beta = 3.7 \times 10^{-10}, \qquad a_d = \frac{m_e c^2}{eH^* R^*} \beta = 1.9 \times 10^{-14}
$$

$$
a_G = m_p \frac{g}{e\beta} = 1.6 \times 10^{-5}, \qquad a_g = m_e \frac{g}{e\beta} = 8. \times 10^{-10},
$$

$$
a_T = \frac{kT^*}{eH^* R^* \beta} = 3.5 \times 10^{-9}.
$$

m_p, m_e are the proton and electron mass respectively.

All these coefficients are small. It means that dynamic equations describing global motion of ionized gas near the star are equations with small parameter before the highest derivative. These parameters for magnitezed planet of solar system, for example, for Earth and Jupiter have apprixametely the same values.

It is very important that electromagnetic terms dominate only in the case of rarefied collisionless gas. Electromagnetic terms have different signs for protons and electrons, and collisions of these species compensate cotributions of electromagnetic terms into the total momentum. Thus, electromagnetic structures, generated by electromagnetic terms of equations (6), (7) appear only in upper layers of stellar atmosphere and other cases of collisionless plasmas.

In the zeroth approximation equations (6), (7) reduce to the equations

$$
n_+ \left(\frac{\mathbf{e}}{\beta} + \mathbf{w}_+ \times \mathbf{h} \right) = 0, \qquad n_- \left(\frac{\mathbf{e}}{\beta} + \mathbf{w}_- \times \mathbf{h} \right) = 0 \tag{8}
$$

which are to be solved together with Maxwell equations (1)-(3). Solving these equations, one determines separation of near-stellar space into a vacuum region V_0 and regions V_+, V_- filled by only protons and by only electrons respectively [17, 7, 8]. The zeroth approximation of cold collisionless completely ionized gas is a very important stage in investigations of the stellar magnetosphere This fact is known for the neutron star magnetosphere, where electromagnetic processes dominate in evident way [14, 15, 6, 16, 7, 8, 17]. But this fact looks rather unexpected in the case of the sunlike star. In the case of dipole magnetic field the charged regions V_+, V_- form polar caps (dome) and equatorial belt. The belt and cap have opposite charges. If the rotational axis $\mathbf{\Omega}$ of the star is parallel to the magnetic moment μ, the cap has negative charge. If they are antiparallel $\mu \uparrow\downarrow \mathbf{\Omega}$, the cap has positive charge. Cap and belt are separated by vacuum region V_0, where there is a longitudinal electric field. Characteristic potential difference Φ between the cap and the belt is of the order $\Phi = ER^* = \beta R^* H^* = 1.5 \times 10^8$V. It is rather strong electric field, which enables to accelerate charged particles and heat the ionized gas.

As the next (first) approximation one should consider the equations

$$a_T \nabla' (t_+ n_+) = n_+ \left(m_p \frac{\mathbf{g}}{e\beta} + \left(\frac{\mathbf{e}}{\beta} + \mathbf{w}_+ \times \mathbf{h} \right) \right)$$

$$a_T \nabla' (t_- n_-) = n_- \left(\frac{\mathbf{e}}{\beta} + \mathbf{w}_- \times \mathbf{h} \right)$$

describing influence of thermal particle motion. Qualitively this process leads to diffusion and heating of caps and belt. This process is especially intensive, if the gas is dense and interaction of positively and negatively charged species is essential. As a result a hot gas envelope appears. This hot invelope is an origin of the stellar wind.

2 Stellar wind

Generally, the charged particles move in the electric field so that the electric field is compensated by the electric charge redistribution. The complete compensation of the longitudinal electric field is possible only inside the rigidly rotating conducting body. In the case of differential rotation the longitudinal electric field cannot be compensated. It generates currents which heat the ionized gas. These currents have the same nature as the induced currents, i.e. they are generated by alternating magnetic flux in coducting body. They depends mainly on time derivative of the magnetic flux and slightly on the shape of magnetic field lines. The induced current generates heating of the conducting body, and observed temperature of the heating is large at that place, where the conducting gas density is low.

It is well known [?] that the solar wind may be explained as a result of the solar upper atmosphere heating . But the reason of this heating is not yet clear completely. We show that the heating of the upper atmosphere of magnetized star may be explained as a result the heating by induced electric currents.

Let us consider layer $\mathcal{L}$ of the stationary stellar atmosphere between the polar angles $\frac{\pi}{2} - \vartheta$ and $\frac{\pi}{2}$. ϑ is supposed to be small, for instance $\vartheta = 0.1$. The second thermodynamic principle for the volume $V = 2\pi r^2 \vartheta a$, having fixed number of particles $N = nV$ gives the relation

$$\frac{3}{2} \frac{d(kT)}{dr} + \frac{kT}{r^2 v} \frac{d(r^2 v)}{dr} = \frac{2\pi r^2 \vartheta}{J} q(r), \qquad q(r) = \frac{\sigma \Phi^2}{r^2 \vartheta^2} \tag{9}$$

where $q(r)$ is thermal power per unit volume, given up inside volume V. $J = 2\pi\vartheta n v r^2$ =const is the flux of particles in $\mathcal{L}$. The power $Vq(r) = \Phi I$ is determined by the electric current $I = 2\pi\sigma r a \Phi / (r\vartheta)$, orthogonal to equator. $\Phi = \Phi(r)$ is the potential difference between the equator and upper edge of $\mathcal{L}$ at the point r. σ is electric conductivity. The radial size a of V can be expressed via $N = 2\pi\vartheta n a r^2$ =const and the flux J of particles in $\mathcal{L}$ by means of relation $a = Nv/J$.

Another dynamic equation (for the gas velocity v) has the form

$$\frac{dv}{dr} = -\frac{r^2}{\mu}\frac{d}{dr}\left(\frac{kT}{r^2 v}\right) - \frac{1}{v}g_r, \tag{10}$$

where g_r is the gravitational acceleration on the distance r. Equations (9), (10) considered to be dynamic equations are invariant with respect to transformation $J \to \kappa J, \quad q(r) \to \kappa q(r)$, where κ is an arbitrary parameter. It means that the heating intensity acts only on the flux J, whereas the temperature profile depends very slightly on the heating intensity.

From physical point of view the stellar wind may be considered to be an escape of energetic molecules of the hot stellar envelope from the stellar gravitational field. For instance, gravitational energy $E_g = \mu g R^*$ of the hydrogen molecule in the solar gravitational field ($\mu = 1.7 \times 10^{-24}$g, $g = 2.7 \times 10^4$cm/s, $R^* = 7 \times 10^{10}$cm) is $E_g = 3.2 \times 10^{-9}$erg. At the same time its thermal energy $\frac{3}{2}kT = 2\times 10^{-10}$erg ($T = 10^6$K) is less only by one order. Practically the solar corona temperature is determined by the balance between the heating intensity and the cooling by means of energetic particles escape. This escape depends on the ratio E_g/kT very strongly (exponentially). Essentially more higher temperature is impssible, because of more intensive cooling conditioned by more intensive escape. The chromosphere temperature (10^4K) is also impossible for upper collisionless solar atmosphere, because of heating by induced currents. This heating is rather intensive, even if the Sun has no regular magnetic field. Irregular solar magnetic field (about 1Gs) generates induced currents in the differentially rotating envelope more intensively, than the regular one.

Let us evaluate mean value of the squared potential Φ^2 in (9), taking into account that asymptotic solution of dynamic equations has the form

$$kT = Br^{-\frac{4}{3}} + O\left(r^{-2}\right), \qquad v = v_\infty + \frac{gR^2}{v_\infty}r^{-1} + O\left(r^{-2}\right),$$

where B, v_∞ are integration constants, and g is gravitation acceleration on the stellar surface.

Let V' be volume of $\mathcal{L}$ between the points R and $r_\infty \gg R$. On one hand, the total energy of V' is constant, because one neglects heat conductivity and radiation loss. On the other hand, in time

$$\tau = \frac{a_s}{v_s} = \frac{a_\infty}{v_\infty} = \frac{N}{J}$$

the volume $V_s = 2\pi R^2 a_s \vartheta$ enter in V', having total energy $E_s = V n_s \left(\frac{3}{2}kT_s + m_p\frac{v_s^2}{2} - m_p g R\right)$, the volume $V_\infty = 2\pi r_\infty^2 a_\infty \vartheta$ goes out from V', having total energy $E_\infty = V n_\infty m_p \frac{v_\infty^2}{2}$, and besides the volume V' obtains the thermal energy $\tau \int_R^\infty 2\pi q(r) r^2 dr$. The balance equation has the form

$$\frac{3}{2}kT_s + m_p\frac{v_s^2}{2} - m_p g R + \frac{Q}{J} = m_p\frac{v_\infty^2}{2}, \qquad Q = 2\pi\int\limits_R^\infty \frac{\sigma\Phi^2}{\vartheta^2}dr \tag{11}$$

where T_s, v_s are values of variables T, v at the stellar surface, v_∞ is the value of velocity v at r_∞. For the Sun the values of T_s, v_s, v_∞, J are known from observations, and one can determine the value of the quantity Q for magnetized sunlike star.

Let the potential Φ be the fraction α of the total potential Φ_0 between the ends of the same magnetic field line. One of ends is placed on the stellar surface and other is placed on equator. The potentials Φ and Φ_0 are defined by the relation.

$$\Phi = \alpha\Phi_0 = \alpha\frac{(\Omega-\omega)\,R^5H^*}{cr^3} = \alpha\frac{\Omega\,(x^2-1)\,R^2H^*}{cx^5}, \qquad r = Rx \tag{12}$$

where the angular velocity ω of moving gas has the form $\omega = \Omega R^2/r^2$ that is connected with conservation of the angular moment $M_\varphi = m_p n\omega r^2$ =const. Using (12), one can calculate the heating Q defined by the relation (11)

$$Q = 2\pi\int\limits_1^\infty \frac{\sigma R}{\vartheta^2}\left(\alpha\frac{\Omega\,(x^2-1)\,R^2H^*}{cx^5}\right)^2 dx = \frac{16}{315}\pi\alpha^2\frac{\sigma R^5\Omega^2H^{*2}}{\vartheta^2c^2} \tag{13}$$

Taking for the stellar wind the solar wind parameters at the Earth orbit: concentration $n = 7\text{cm}^{-3}$, velocity $v = 4.5\times10^7\text{cm/s}$, distance $r_\infty = 1.5\times10^{13}\text{cm}$, $\vartheta = 0.1$, one obtains for the flux $J = 4.5\times10^{35}\text{s}^{-1}$. Choosing the star parameters $R = 7.\times10^{10}\text{cm}$, $g = 2.7\times10^4\text{cm/s}^2$, $\Omega = 3.\times10^{-6}\text{s}^{-1}$, $T_s = 6.\times10^3\text{K}$, $\sigma = 1.7\times10^9\text{s}^{-1}$, one can calculate the mean fraction α of the total potential Φ_0 which takes part in the stellar wind formation. From relations (11) and (13) one obtains that $\alpha = 2\times10^{-3}$. This is rather small part of the total potential, and one can hope that consideration of thermal conductivity and radiational loss does not change the result that induced currents generated by the rotation of magnetized star can explain heating the upper atmosphere and appearance of the stellar wind. The result was estimated for specific form of the magnetic field (dipole field). It is evident that it is valid for any axially symmetric magnetic field. Apparently it is valid for any magnetic field due to specific properties of induced currents.

3 Jets

We have considered the case, when the angular velocity ω of the ionized gas is less, than the angular velocity Ω of the star. In this case the rotational energy of the star is transmitted to the gas via induced longitudinal electric field. In the case, when the star has a conducting accretion disk whose angular velocity ω is larger, than the stellar angular velocity Ω, the rotational energy of the disk may be transmitted to the star via longitudinal electric field. In this case the accretion disk gives energy to longitudinal electric field and increases it, in general. In the special case of the dipole magnetic field, when $\mathbf{\Omega}\uparrow\uparrow\mu$, the electron cap V_- of zeroth approximation has clear jetlike structure. Its shape is described in spherical coordinates (r, ϑ, φ) by the equation [16, 17].

$$\vartheta = C\left(\frac{r}{R^*}\right)^{0.4} \qquad \text{for}\ \ 10 < \frac{r}{R^*} < 10^4, \qquad C = \text{const}$$

This electron cap is a stable structure, generated by the dipole magnetic field and the quadrupole electric field, generated by it. If the longitudinal electric field appears inside the electron cap as a result of the conducting accretion disk action, electrons of the cap are accelerated, and a relativistic jet appears. Correlation between the jets and existence of accretion disk is known from observational data [12]. For formation of jets one needs two things: (i) rotating central body with the dipole magnetic momemt aligned with the rotational axis, and (ii) superrotating collisionless conducting medium (accretion disk). Such conditions are rather common in astrophysics, and one can observe jets generated by different astrophysical objects from neutron stars to galaxies. For explanation of relativistic particles and sharp collimation of their motion, needs the longitudinal electric fields. MHD neglects these electric fields and hardly can explain origin of relativistic jets.

References

[1] Begelman, M.C. 1998, *Ap. J.* **473,** 963.

[2] Blandford, R.D. and Payne, D.G., 1982, *MNRAS,* **199,** 883.

[3] Coppi, P. 1999, astroph-ph/9903162

[4] Goldreich, P. and Julian, W.H., 1969, *Ap. J.* **157**, 869.

[5] Jackson, E.A., 1976, *Ap. J.* **206,** 831.

[6] Julian, W.H., 1873, *Ap. J.* **183,** 967.

[7] Krause-Polstorf, J. and Michel, F.C. 1985a, *MNRAS,* **213**, 43.

[8] Krause-Polstorf, J. and Michel, F.C. 1985b, *Astron. Astrophys.,* **144**, 72.

[9] Koide, S., Shibata, K. and Kudoh, T. 1998, *Ap. J.* **495,** L63.

[10] Luceck, S.G. and Bell, A.R. 1997, *MNRAS,* **290,** 327.

[11] Michel, F.C., 1973, *Ap. J.* **180**, 207.

[12] Mirabel, I.F. and Rodriguez L.F, 1999, astroph-ph/9902062.

[13] Parker, E.N., 1956, Astrophys. J. **128**, 664.

[14] Pilipp, W.G., 1974, *Ap. J.* **190**, 391.

[15] Rylov, Yu.A. 1976, *Soviet Astron. AJ*, **20**, 23.

[16] Rylov, Yu.A. 1977, *Astroph. and Space Sci.* **51**, 59.

[17] Rylov, Yu.A. 1985, *Astroph. and Space Sci.* **117**, 5.

[18] Rylov, Yu.A. 1988, *Astroph. and Space Sci.* **143**, 269.

[19] Spruit, H.C.,Foglizzo, T., Stehle, 1997, *MNRAS*, **288,** 333.