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A TWO-DIMENSIONAL MODEL OF THE MAGNETOSPHERE OF A COMPACT STAR WITH AN ACCRETION DISC†

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The magnetosphere of a compact stellar object with an accretion disc is considered. Using the method of conformal mapping, the shapes of the magnetosphere and the accretion disc and, also, the configuration of the magnetic field within the limits of the magnetosphere are obtained in a self-consistent manner in the approximation of ideal magnetohydrodynamics. The dependence of the solution on the parameters is investigated. The proposed model is related to neutron stars (magnetars, in particular) and white dwarfs. © 2004 Elsevier Ltd. All rights reserved.

The formation of a compact object is the final stage in the evolution of a star in which the nuclear reactions have already been completed and the stellar matter starts to be compressed (collapses) under the action of gravitational forces [1]. As a result, a star of sufficiently small mass becomes a white dwarf, that is, an object, the equilibrium of which is ensured by the equality of the gravitational forces and the forces due to the pressure of the degenerate electron gas. The maximum value of the mass of a white dwarf (the Chandrasekhar limit) is about 1.46 times the mass of the Sun. If the star has no sources of internal energy and its mass exceeds the Chandrasekhar limit, it will collapse until the atomic nuclei come into contact and a gigantic atomic nucleus develops with a density of the order of 10^{14} g/cm^3 and a size of approximately 10 km. This is a neutron star [2].

The combination of large mass and small dimensions leads to the fact that a *strong gravitational field* surrounds a compact star, which is capable of capturing matter from the interstellar medium or from a conventional star situated close to it (the companion in the pair). In some cases, matter, approaching a compact star, follows the magnetic field lines and is directed to the poles, where the gravitational energy of the matter is transformed into X-ray radiation. However, by no means all of the observed data can be successfully explained by this scenario. In particular, it has been shown that, if the matter captured by the gravitational field possesses a sufficiently large rotational moment, then it twists around the compact object, forming a rotating annular disc which is called an accretion disc (AD) [3, 4]. The dashed lines Γ in Fig. 1 schematically depict its sections. Up to the present time, a large number of different models of the processes occurring in the surroundings of such stars have been proposed [5]. However, the mechanisms of accretion will not be considered in this paper; our aim is to investigate the magnetic field of the star–accretion disc (AD) system.

The existence of *strong magnetic fields* is the second special feature of compact objects. The field strength on a neutron star reaches a value of $\sim 10^{12}$ Gauss. In recent years, data have appeared on young neutron stars with magnetic field strengths of 10^{15} Gauss, which have acquired the name magnetars [6, 7]. Such a strong field exerts an enormous effect on the motion of the plasma close to the star.

Furthermore, it is important to note that the AD itself possesses an *intrinsic magnetic field* which also penetrates a certain domain on both sides of the AD, forming a corona (C in Fig. 1) [18–10]. The domain of the space around the star, occupied by the magnetic field of the compact star and the corona of the AD, is called the magnetosphere and its boundary is called the magnetopause (S in Fig. 1).

The investigation of the magnetosphere of compact stars (its shape, dimensions, configuration and the magnitude of the field within it) is one of the current problems in astrophysics. Many publications indicate that it is, in fact, the magnetic field which is responsible for the different phenomena observed in compact stars, such as X-ray emission and the ejection of matter [7–12]. Observations show that, in a number of cases, the X-ray emission comes from domains located above the internal part of the AD,

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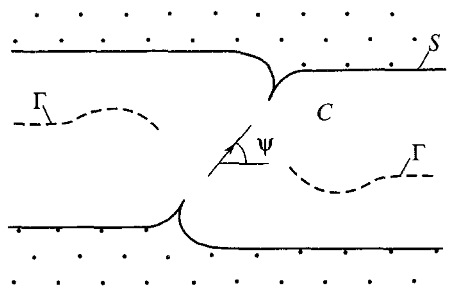

Fig. 1

that is, from domains where interaction occurs between the field of the star and the field of the AD [13–17]. A knowledge of the magnitude of the field in different parts of the magnetosphere and the internal radius of the AD enables one to obtain reliable quantitative estimates of the liberation of energy in the corona of the AD, and a knowledge of the characteristic dimensions of the magnetosphere can help in explaining the distinctive features of the periodic emission from compact stars.

The theory of functions of a complex variable (see [18–21], etc.) has been used for a long time to solve two-dimensional problems in cosmic magnetohydrodynamics. In particular, an example has been given of the solution of problems involving the flow around bodies which have a magnetic field and the flow of a conducting gas, and the problem of the shape of the Earth's magnetosphere has also been solved [22–24]. The problem of the configuration of the magnetic field close to an accreting compact star possessing a multipolar magnetic moment [25] and of a star possessing a dipole magnetic moment, without taking account of the external boundary of the magnetosphere and in the approximation of a planar AD, has been considered [26]. The shape of a magnetosphere with a planar AD when there is an external boundary has been calculated in [27]. The question of the shape of an AD has been investigated in [28, 29]. An exact solution for the shape of a magnetosphere without an AD with an arbitrary exponential pressure distribution, and also the shape of the magnetosphere of a star which is rotating under hypersonic conditions has been found [21]. The configuration of the magnetic field in the magnetosphere of a star without an AD has been investigated [30].

The problem of the magnetosphere of a compact object which possesses a dipole magnetic moment is considered below for the case when there is a disc accretion. The plasma surrounding the magnetosphere is characterized by a pressure $p = p_0 = \text{const}$ and a high magnetic Reynolds number. The mathematical formulation of the problem is given in Section 1, and the method for solving it in Section 2. The shape of the magnetopause and the shape of the AD are calculated for an arbitrary angle of inclination ψ of the magnetic axis of the star to the plane of the AD and also the configuration of the magnetic field within the limits of the magnetosphere. The dependence of the solution obtained on the input parameters is analysed in Section 3. Certain limiting cases are considered which reduce to analytical solutions, which are already known, and the results are compared with the estimates of other authors obtained on the basis of observed data.

1. FORMULATION OF THE PROBLEM

The existence of a strong magnetic field and a comparatively rarefied plasma is found to be a common feature in the space around compact objects. Here, the magnetic force predominates over the other forces: the pressure gradient, the inertial force, the gravitational force, etc. The strong field approximation [31] is therefore applicable in the treatment of such problems: the solutions of the equations of magnetohydrodynamics are sought in the form of series containing small parameters, such as the pressure gradient to the magnetic gradient ratio, etc. The solution for the magnetic field is force-free or potential in the zeroth order with respect to the small parameters.

In the formulation of the problem being considered, a highly conducting plasma flows around a certain "empty" region of space. This region of space can be said to be empty in the following sense: the magnetic field enclosed in it is so strong that it compensates itself in the plasma as in a vacuum, that is, it can be calculated in the potential approximation. Furthermore, we shall assume that the interface S between the plasma flow and the domain being considered is determined by the equality of the magnetic and gas pressures.

Thus, the physical picture can be described by the following mathematical model. A compact star is simulated by a point dipole with a moment

$$\mathbf{m} = me^{i\psi} \tag{1.1}$$

where ψ is the angle between the direction of the axis of the dipole and the plane of the AD far from the star, where the position of the AD is determined by the condition for the flow of matter from the star-companion. The magnetic field is potential, that is, it is described by the equations

$$\mathrm{div}\mathbf{B} = 0, \quad \mathrm{rot}\mathbf{B} = 0 \tag{1.2}$$

In the magnetopause S, the magnetic pressure is balanced by the gas pressure

$$B^2/(8\pi)|_S = p \tag{1.3}$$

Outside the magnetosphere, $\mathbf{B} = 0$, and the equations of conventional gas dynamics are applicable. We will assume that the field of the star does not penetrate either through the boundary S or through the AD Γ, that is,

$$\mathbf{Bn}|_{S,\Gamma} = 0 \tag{1.4}$$

We will assume that the magnitude of the magnetic moment $m = m_0$, the angle ψ of inclination of the dipole to the plane of the AD and the values of the gas pressure are given. It is required to find the shape of the magnetopause S, the shape of the AD Γ and, also, the magnetic field $\mathbf{B}$ within the limits of the magnetosphere.

It is also assumed that the magnetic pressure on the two sides of the AD is balanced, that is, the quantity $|\mathbf{B}|$ does not change on passing across the AD. There is one further parameter characterizing the formulation of the problem and these are the magnetic field flows, departing from both sides of the AD to infinity. In order to understand the origin of these flows, it can be imagined that the configuration of the magnetic field being studied arose as the result of the arrival of an ideally conducting layer, which represents the AD, from infinity. In the three-dimensional formulation, there is an aperture at the centre of the AD, inside which the star is located. In the two-dimensional formulation, there is also an aperture which is the space between the left and right-hand parts of the AD. According to condition (1.4), the magnetic field does not intersect the AD but a non-zero magnetic flux can pass through the aperture in the AD.

2. SOLUTION OF THE PROBLEM

The essence of the method proposed earlier [22, 24] for solving problems with a previously unknown boundary is as follows. For any fixed position of the boundary S, the solution of Eqs (1.2) with conditions (1.1) and (1.4) is unique, and condition (1.3) is therefore sufficient to determine the shape of S.

We will consider the plane case

$$\mathbf{B} = (B_x(x, y), B_y(x, y), 0)$$

Suppose $z = x + iy$ is the complex plane. It is then convenient to describe the field using the potential $F(z)$, which is an analytic function associated with the vector $\mathbf{B}$ by the relation [31]

$$\mathbf{B} = B_x + iB_y = -i(dF/(dz))^* \tag{2.1}$$

The asterisk denotes the complex conjugate and the field lines are the level lines of the real part of the potential, that is, they are determined from the condition

$$\mathrm{Re}F(z) = \mathrm{const} \tag{2.2}$$

We will assume that there is a conformal mapping of the domain occupied by a magnetosphere with an unknown boundary S in the z plane onto a certain known simple domain with a specified boundary S' in the auxiliary plane $w = u + i\upsilon$. It is required here that the mapping $w(z)$ should transfer the origin of the coordinates $z = 0$ into the origin of the coordinates $w = 0$ and that the angle of inclination of the dipole should be preserved. Then, on constructing the potential $F(w)$, which is created by the dipole $\mathbf{m}$ in the plane w such that the boundary S' is a field line, and knowing the dependence $w = w(z)$, it is possible to obtain the magnetic field vector and, consequently, the distribution of the field lines in the z plane using formulae (2.1) and (2.2) (Fig. 2). Hence, in order to solve problem (1.1)–(1.4), it is necessary to construct the potential $F(w)$ and the mapping $w(z)$.

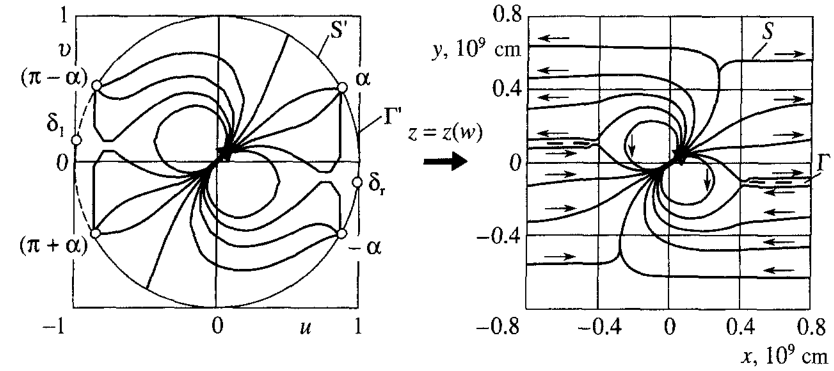

Fig. 2

We shall make use of the dimensionless variables which are obtained by dividing the dimensional quantities: the magnetic moment m, the pressure p, the magnetic field B and the distances x and y, by $m_0, p_0, B_0 = p_0^{1/2}$ and $L_0 = m_0^{1/3} p_0^{-1/6}$ respectively.

We will choose the unit circle as the auxiliary domain in the w plane. The required potential then has the form

$$F(w) = iQ\left(\ln\frac{w - e^{i\alpha}}{we^{i\alpha} - 1} + \ln\frac{w - e^{i(\pi - \alpha)}}{-we^{i(\pi - \alpha)} + 1}\right) + ie^{-i\psi}w + \frac{ie^{i\psi}}{w} \tag{2.3}$$

Here Q is the "magnetic mass" [24], a quantity which characterizes the intrinsic magnetic field of the AD. On changing to dimensional variables, it is necessary to multiply by the dimensional quantity $Q_0 = p_0^{1/3} m_0^{1/3}$; α is the free parameters of the problem such that the arcs $(-\alpha, \alpha)$, $(\pi - \alpha, \pi + \alpha)$ of a unit circle in the w plane are converted under the mapping into the right and left-hand branches of the AD in the z plane while the arcs $(\alpha, \pi - \alpha)$ and $(\pi + \alpha, 2\pi - \alpha)$ in the w plane correspond to the magnetopause in the z plane. Note that the actual magnetic field of the AD has an exceedingly complex structure [8–10]. Since the aim of this paper is to calculate the parameters of the magnetosphere as a whole, we will confine ourselves to taking account of the large scale scale magnetic field of the AD, characterizing it by means of a single parameter Q and not going into its fine structure.

Condition (1.3) gives the ordinary differential equation for finding the real part $x(\varphi)$ of the function of the mapping for the magnetopause. Here, φ is the argument of a point in the w plane. The equation was solved numerically using the Runge–Kutta method. In order to calculate the shape of the magnetopause, it is still necessary to find the imaginary part of the mapping, that is, the function $y(\varphi)$. We will use the fact that the mapping is conformal, that is, the function $z(w)$ is analytic. Consequently, its real and imaginary parts are harmonically conjugate functions. Using the expansion of $x(\varphi)$ in a Fourier series and taking the harmonically conjugate series, we find $y(\varphi)$ for the magnetopause. Thus, the external boundary of the magnetosphere has been constructed.

We will now determine the position of the AD, that is, we will find the function $y(\varphi)$ on that part of the circle $|w| = 1$ which corresponds to the AD. In the simplest formulation of the problem [25], the AD is replaced by an infinitesimally thin layer which separates the counter directed field lines. If the layer is fixed and the forces acting on its two sides are balanced, then the equality

$$|B^+| = |B^-|$$

holds at each point of the layer, where the plus and minus signs correspond to the upper and lower edges of the cuts Γ of the complex z plane.

We will now consider the arc $(-\alpha, \alpha)$ in the auxiliary w plane which corresponds to the right-hand branch of the AD. We denote the point of an arc corresponding to the internal boundary of the AD by δ_r. It follows from what has been said that the modulus of the field B as a function of the angle φ in the w plane has an extremum at the point δ_r. On constructing the relation $B = B(e^{i\varphi})$, where $\varphi \in (-\alpha, \alpha)$, using the potential (2.3) and relations (2.1), we find the point δ_r.

The arc (δ_r, α) is mapped onto the upper side of the AD and the arc $(\delta_r, -\alpha)$ is mapped onto the lower side. Consequently, a function $g(\varphi)$ must exist which maps the interval (δ_r, α) onto the interval

$(\delta_r, -\alpha)$ such that

$$z(e^{i\varphi}) = z(e^{ig(\varphi)}) \tag{2.4}$$

that is

$$|B(e^{i\varphi})| = |B(e^{ig(\varphi)})|$$

This last equality, written using relations (2.1) and (2.3) as a function of w, gives the dependence $g(\varphi)$ for the points of the arc $(-\alpha, \alpha)$. Similarly, we find δ_l, the argument of the point corresponding to the internal boundary of the left-hand section of the AD.

From condition (2.4), it follows that

$$x(\varphi_0) = x(g(\varphi_0)) \tag{2.5}$$

where φ_0 is a point of the arc $(-\alpha, \alpha)$.

We find expressions for $x(\varphi_0)$ and $x(g(\varphi_0))$ using Schwartz's formula [32]

$$z(w) = -\frac{1}{2\pi i}\int_0^{2\pi} y(\varphi)\frac{e^{i\varphi}+w}{e^{i\varphi}-w}d\varphi \tag{2.6}$$

We write it for the points of the unit circle $w = e^{i\varphi_0}$ and separate out the real part to obtain

$$x(\varphi_0) = \frac{1}{2\pi}\int_0^{2\pi} y(\varphi)\,\mathrm{ctg}\frac{\varphi-\varphi_0}{2}d\varphi \tag{2.7}$$

We denote the imaginary part of the function, corresponding to the right-hand (left-hand) section of the AD, by $y_{r(l)}(\varphi)$ and the imaginary part of the mapping function, corresponding to the upper (lower) boundary of the magnetosphere, by $y_{t(b)}(\varphi)$. Expression (2.7) then takes the form

$$x(\varphi_0) = \frac{1}{2\pi}\left[\int_{-\alpha}^{\alpha} y_r(\varphi)\,\mathrm{ctg}\frac{\varphi-\varphi_0}{2}d\varphi + \int_{\alpha}^{\pi-\alpha} y_t(\varphi)\,\mathrm{ctg}\frac{\varphi-\varphi_0}{2}d\varphi + \right.$$
$$\left. + \int_{\pi-\alpha}^{\pi+\alpha} y_l(\varphi)\,\mathrm{ctg}\frac{\varphi-\varphi_0}{2}d\varphi + \int_{\pi+\alpha}^{2\pi-\alpha} y_b(\varphi)\,\mathrm{ctg}\frac{\varphi-\varphi_0}{2}d\varphi\right] \tag{2.8}$$

The expression for $x(g(\varphi_0))$ is written in similar manner (in the equality (2.8), it is sufficient to replace φ_0 by $g(\varphi_0)$).

We assume that $y_r(\varphi)$ and $y_l(\varphi)$ are slowly varying functions, that is, for each chosen φ_0, we will assume that

$$y_{r,l}(\varphi) = \mathrm{const}(\varphi_0) = C_{r,l}(\varphi_0)$$

This assumption enables us to move these functions out of the integrand. Then, by virtue of relations (2.5), on the equating $x(\varphi_0)$ and $x(g(\varphi_0))$ we obtain an equation in the two constants $C_r(\varphi_0)$ and $C_l(\varphi_0)$. Since the problem is symmetric with respect to the origin of coordinates, we have

$$C_l(\varphi_0) = -C_r(\varphi_0) \tag{2.9}$$

which reduces condition (2.5) to an equation in a single unknown for each value of φ_0. Using expression (2.8), we then find the corresponding values of $x(\varphi_0)$. The pairs $(x(\varphi_0), C_r(\varphi_0))$, where $\varphi_0 \in (\delta_r, \alpha)$, give the position and shape of the right-hand section of the AD and the pairs $(x(\varphi_0), -C_r(\varphi_0))$, where $\psi_0 \in (\pi - \alpha, \delta_l)$, give the position and shape of the left-hand section of the AD.

An example of a calculation is shown in Fig. 3 where the shape of the left-hand section of the AD is shown for different scales along the abscissa and the ordinate. Note that the AD is almost planar, that is, the magnetic field does not have a large effect on the shape of the AD.

The system of functions $y(\varphi)$ has thereby been completely determined for all $\varphi \in (0, 2\pi)$. Now, by making use of Schwartz's formula (2.6), we find the function $z(w)$ in the whole circle $|w| \leqslant 1$. Knowing

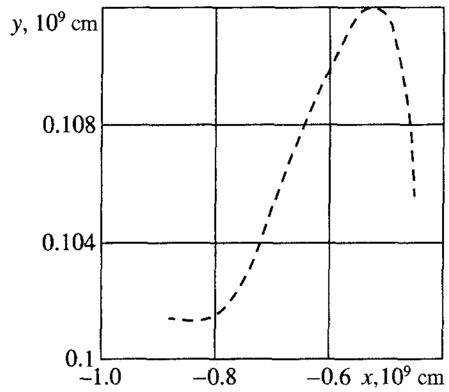

Fig. 3

the potential $F(w)$ and the mapping $z(w)$ which converts the unit circle in the w plane into the magnetosphere in the z plane, we obtain the configuration of the magnetic field in the z plane.

In order to return to dimensional variables, it is necessary to specify the values of the magnetic moment m_0 and the pressure p_0 of the interstellar gas on the boundary of the magnetosphere. To do this, we shall make use of existing data [5] and we choose $m_0 = 10^{30}$ Gauss.cm^3 and $p_0 = 1.38 \times 10^6$ dyne/cm^2 which corresponds to the parameters of a typical neutron star.

The pattern of the field lines in the w and z planes for the values of the parameters $\alpha = \pi/6$, $Q = 1/2$, $\psi = \pi/4$ is shown in Fig. 2 for the example. Note that the method which has been described enables one to obtain numerical estimates of the magnetic field strength at any point of the magnetosphere.

3. DISCUSSION OF THE RESULTS

Estimation of the reliability of the solution. By varying the values of the three parameters α, ψ and Q, it is possible to reduce the solution obtained to the results of other authors.

A magnetosphere without an AD corresponds to the case when $\alpha = 0$ and $Q = 0$, and, during the mapping, the whole of the auxiliary unit circle becomes the external boundary of the magnetosphere (Fig. 2). On directing the magnetic dipole upwards, that is, on putting $\psi = \pi/2$, we obtain a potential F which is identical with that considered previously in [30] for the corresponding case and a shape of the magnetosphere without an AD, calculated by the method of conformal mappings, which is also identical with that obtained by another method in [33].

Note that the parameters α and Q are interconnected. They can be non-zero or vanish simultaneously. Actually, the case when $\alpha \neq 0$ corresponds to the existence of an AD. Since a real AD always possesses a magnetic field, the parameter Q, which characterizes this quantity, must be non-zero. This is reflected in formula (2.3) for the magnetic potential where, when one of the parameters α and Q vanishes, the other automatically disappears.

The fact that the characteristic dimensions of the magnetosphere which have been obtained are in good agreement with the estimates obtained by others is evidence of the reliability of the solution presented. For instance, according to the estimates obtained in an analysis of observations of the neutron star 4*U* 1907 + 09 using the IXAE space probe, the star is surrounded by a magnetosphere with a characteristic radius $r_m \sim 0.4 \times 10^9$ cm and the AD begins at a distance $r_d \sim 10^8 - 10^9$ cm from the star [15]. Results obtained for a standard neutron star, that is, for a star with a magnetic moment $m_0 = 10^{30}$ Gauss.cm^3 and a gas pressure on the boundary of the magnetosphere $p_0 = 1.38 \times 10^6$ dyne/cm^2 (the data are taken from [5]) which give a characteristic size of the magnetosphere of $r_m \approx 0.6 \times 10^9$ cm and a distance from the star to the AD of $r_d \approx 4 \times 10^8$ cm, are presented on the right-hand side of Fig. 2.

It can therefore be concluded that the reliability of the results obtained is confirmed by the available calculations and the observed data. Note that a list of known neutron stars which are similar to 4*U* 1907 09, that is, a star to which the proposed model can be applied, is given in [15].

Investigation of the structure of the magnetosphere. We will now consider the special features of the field within the magnetosphere. For simplicity, we shall consider the case when the magnetic axis of the star is perpendicular to the plane of the AD: $\psi = \pi/2$. In this case, the structure of the magnetic

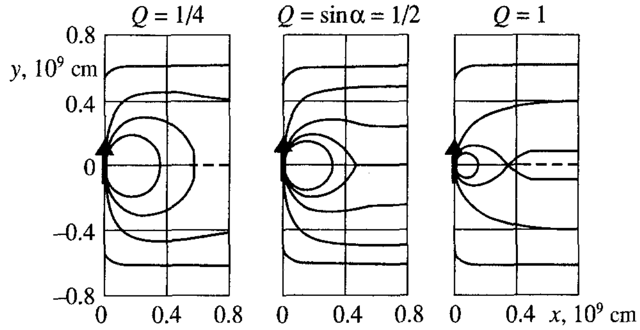

Fig. 4

field becomes symmetrical about the Oy axis and the AD acquires a planar shape. The three version of the structure of the field shown in Fig. 4 correspond to three values of the parameter Q for a fixed $\alpha = \pi/6$ (from symmetry considerations, only the right-hand sides of the magnetospheres are shown). It is clear that the configuration of the field within the magnetosphere changes when there is an increase in the magnetic field of the AD.

We will now consider the question of the arrangement and number of zero points of the magnetic field. These points play an important role in the acceleration of the particles in a plasma [31]. Calculations show that the magnetosphere contains two zero points, which lie in the plane of the AD. Depending on the ratio of the magnetic moment of the star and of the disc, the zero points can be located between the star and the AD (the right-hand part of Fig. 4), coincide with the internal edge of the AD (the middle part of Fig. 4), or lie in the AD (the left-hand part of Fig. 4).

We will now determine for which values of the parameters α and Q a zero point coincides with the internal edge of the AD. It is obvious that the zero points of the field in the w plane correspond to the zero points in the z plane. In fact, the equality

$$\mathbf{B} = -i(dF/(dz))^* = -i(dF/(dw)dw/(dz))^* = 0$$

follows from expression (2.1). The derivative dw/dz is now zero as a consequence of the conformality of the mapping. Consequently, the equality

$$dF/(dw) = 0 \tag{3.1}$$

must be satisfied, which means that the coordinates B_u and B_υ of the magnetic field in the w plane are equal to zero. The potential F in this plane has the analytical form (2.3), which is convenient for analysis. For the fixed value of $\psi = \pi/2$, due to the symmetry of the magnetic field about the Oy axis in the auxiliary w plane, the point (1, 0) corresponds to the start of the neutral layer. On substituting these coordinates into system (3.1) and separating the real and imaginary parts, we obtain a system of two algebraic equations in the two variables α and Q. Its solution shows that a zero point of the field coincides with the internal edge of the AD if the parameters are chosen such that

$$Q = \sin\alpha$$

We will now consider the question as to which the states shown in Fig. 4 will be the most suitable from an energy point of view. For this purpose, we will calculate the force induced by the magnetic field and acting on the internal edge of the AD, that is, we evaluate the integral of the Maxwell stress tensor σ_n [34]

$$\sigma^{xx} = \frac{1}{4\pi}\left(B_x^2 - \frac{1}{2}B^2\right), \quad \sigma^{yy} = \frac{1}{4\pi}\left(B_y^2 - \frac{1}{2}B^2\right), \quad \sigma^{xy} = \sigma^{yx} = \frac{1}{8\pi}B_x B_y$$

along a certain contour, which encompasses the neighbourhood of the internal edge of the AD. Numerical integration shows that, as would be expected, the forces acting along the Oy axis compensate one another in all three cases.

At the same time, in the case of the versions corresponding to the left- and right-hand parts of Fig. 4, there is a force acting along the Ox axis which tends to repel the AD from the star. This force is only absent in the version corresponding to the middle part of Fig. 4. Hence, in the strong magnetic field approximation, that is, in the case when the magnetic force predominates over all other forces, the state for which a zero point of the field coincides with the internal edge of the AD is the equilibrium state. This conclusion is in accord with simple analytical solutions for the magnetic force acting on the edge of a current layer [35].

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