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OVAL OF AURORAE BOREALIS AND THE RING CURRENT IN THE EARTH'S MAGNETOSPHERE

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SUMMARY

Making use of Williams' and Ness' calculations, the position is computed and graphically presented of the boundary of closed lines of force on the night side of the Earth as a fuction of the field in the magnetosphere tail and of the ring current value. Observations of the southern boundary of the aurora oval allowed a direct determination of the magnetic flux of the ring current. On the other hand, the same flux is calculated as a function of ring current parameters in the Akasofu and Cain model. Comparison of the results of calculations leads to the conclusion that during magnetic storms the ring current is at a distance of $\sim$ 3-3.5 Earth's radii. With the increase of the ring current field, the proton belt increases at the expense of the withdrawal of its outer boundary and a redistribution (increase) of the pitch-angles takes place.

* * *

The discrete forms of the aurora borealis are disposed along an oval whose geomagnetic latitude depends on the local time, namely $\Phi' \sim 67°$ in the hours close to midnight and in the diurnal hours $\Phi' \sim 76-77°$ [1]. The position of the oval depends to a considerable degree on the intensity of polar magnetic disturbances and on the ring current in the Earth's magnetosphere [2-4]. Satellite observations have shown that the oval of aurorae borealis is located at the boundary of the closed lines of force of the geomagnetic field and of the field lines carried away by solar wind into the tail of the magnetosphere [5-8]. Therefore, it can be presumed that the position of the southern boundary of the oval yields with a necessary degree of precision data on boundary of the closed geomagnetic field lines both in the cases of quiet and disturbed magnetic field.

Williams and Ness [9] have calculated the position of the boundary Λ_c of the closed lines of force on the night side of the Earth as a function of the field in the magnetosphere tail, but in the absence of a ring current. In this case, the magnetic flux through a portion of the Earth surface bounded on the night side by a certain geomagnetic longitude interval λ_M, the geomagnetic equator and the latitude Λ_c, can be represented by the expression

$$F_{W-N} = \frac{M\lambda_M}{R_E}\sin^2\Lambda_c, \quad (1)$$

where M and R_E are respectively the magnetic moment and the radius of the Earth.

The accounting for the DR-field of the ring current consists in adding in (1) its magnetic flux

$$\Delta F_R = \lambda_M R_E{}^2\int_{R_E}^{r} H_R r dr. \quad (2)$$

It is assumed that the intensity of the field H_R of the symmetric ring current is known along radial distance r in the plane of the geomagnetic equator and that on the Earth's surface it assumes a value equal to the DR-field. Then from (1) and (2) we obtain the expression for determining boundary Φ_R' of the closed lines of force on the night side, taking into accoun DR-field

$$\sin^2\Phi_R' = \sin^2\Lambda_c + \frac{R_E^3}{M}\int_{R_E}^{r} H_R r\, dr. \quad (3)$$

In calculating the position of Φ_R' on the Earth's surface as a function field N of the tail, use was made of the value of Λ_c from [9] with the preassigned values

$$I_R = \frac{R_E^3}{M}\int_{R_E}^{r} H_R r dr \quad (4)$$

in expression (3). Fig.1 shows graphically the results of the calculations. The upper curve represents the values of Λ_c or Φ_R' in the absence of the ring current ($I_R = 0$).

With the increase of I_R the boundary of the closed lines of force and, consequently, the southern boundary of the aurora oval

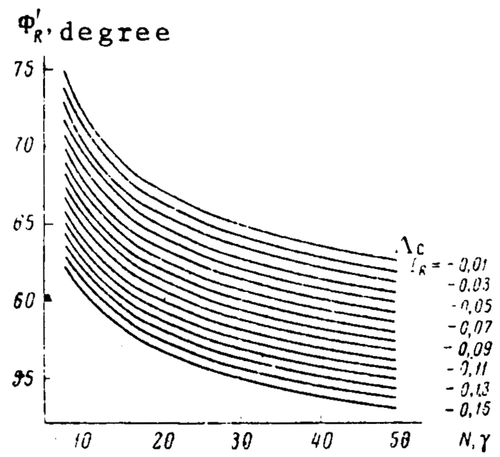

Fig.1

Position of the boundary Φ' of closed lines of force on the night side of the Earth as a function of N field in the magnetosphere tail and the value of the I_R ring current.

on the night side of the Earth is shifted to lower geomagnetic latitudes. This shift is greatest at low values of tail's field.

The quantity I_R may be linked with the parameters of the ring current. Since the magnetic moment M and the Earth's radius R_E are constant, I_R depends on the shape of the curve H_R of the ring current's field intensity along the equatorial radius and on the degree of its extension to greater distances.

Akasofu and Cain [10] computed a function Δf, designating the magnetic field per unit of particle energy density from 1 to 10 R_E depending on the distance r_0 to the maximum of particle density N_0, on the value of g_2, describing the outer boundary of particle distribution in the ring current particle (similarly g_1 describes the inner distribution boundary) and on the constant α characterizing the distribution of pitch-angles of ring current's particles. According to [10], the value of H_R is obtained from the relation

$$H_R = \Delta f N_0 E_0, \qquad (5)$$

where E_0 is the particle energy of the ring current.

Selecting each time N_0E_0 in (5) in such a manner that the field on the Earth's surface assume the value $H_R = 100\gamma$, the values of I_R were calculated for various parameters of the ring current, taking into account its induction part. During computations it was assumed that the induced current flows in a conducting layer at a depth of 500 km from the Earth's surface and that its field is equal to one half of the field H_R on the Earth's surface (the aperiodic variation is $D_{St} = {}^3/_2 H_R$). At $H_R = 100\gamma$ the induction field varies with distance from -50γ (1 R_E) to 0.7γ at 4 R_E, yielding a total contribution $(I_R)_E = 0.0013$. The values of I_R are compiled in Table I with correction for induction for three groups of parameter in each of which one parameter varies, while three remain constant.

Comparison of the position of the boundaries of the aurora borealis oval at different DR intensity with a theoretical model ring current makes it possible to arrive at some conclusions regarding changes in model parameters.

As is shown in recent satellite observations [11,12], the main mass of protons forming the ring current in periods of magnetic storms is located at a distance of 3-3.5 R_E. This is why in a first approximation, a model ring current with parameters $r_0 = 3.2\ R_E$, $g_1 = 2.146$, $g_2 = 0.759$ and $\alpha = 2.0$ (model C according

Values of fixed paramet.	r_0	I_R	Values of fixed paramet.	g_2	I_R	Values of fixed paramet.	α	I_R
$g_1 = 2{,}290$	3,5	−0,072	$r_0 = 3{,}2\ R_3$	2,146 A	−0,005	$r_0 = 3{,}2\ R_3$	1	−0,051
$g_2 = 0{,}419$	4,0	−0,098	$g_1 = 2{,}146$	1,517 B	−0,010	$g_1 = 2{,}628$	2	−0,062
$\alpha = 2{,}0$	4,5	−0,123	$\alpha = 2{,}0$	0,759 C	−0,024	$g_2 = 0.379$	3	−0,069
	5,0	−0,152		0,379 D	−0,074		4	−0,081

TABLE I

to [10]) was adopted for further calculations. In this model the particle distribution is limited by the equatorial distances of 2.2 and 6 R_E and $I_R = -0.022$ at DR = -100γ. If one assumes that during a magnetic storm only the ring current intensity (N_0E_0) varies, while all its other parameters remain unchanged (Δf = const), then according to (4) and (5), $I_R = 2.2 \cdot 10^{-4}\ DR^{\gamma}$. Thus, in the adopted model I_R is known for any DR-field.

We shall determine the field N in the magnetosphere tail from observations of the aurorae borealis.

As a matter of fact, the magnetic flux carried away by solar wind in the tail of the magnetosphere from two polar regions is [13]

$$F = \frac{4\pi M}{R_E} \cos\theta_M \sin^2\theta, \qquad (6)$$

where Θ_M is the polar distance of the oval center and Θ is the distance between the oval boundary and its center. Assuming that the magnetosphere tail has the shape of a cylinder with radius a_t and that the field N distribution in the transverse cross-section of the magnetosphere is uniform, we shall write the same magnetic flux as follows:

$$F = \pi a_t{}^2 N. \qquad (7)$$

Then, from (6) and (7) we obtain

$$N = \frac{4M}{a_t{}^2 R_E} \cos\theta_M \sin^2\theta. \qquad (8)$$

From observations of aurorae borealis the southern boundary of oval Φ' [1] are known, and consequently so are Θ_M and Θ for various indices Q of magnetic activity from 0 to 6. For Q equal to 3 and 5, known also is the behavior of Φ' with the variation of the DR-field [1]. For the night side of the Earth such a dependence is shown in Fig.2.

Let us take a_t respectively equal to 21.2 and 19.9 R_E for Q = 3 and Q = 5 [13]. In this case the theoretical values of the oval boundary taken down from the curves of Fig.1 on the basis of known I_R and N calculated from (8), coincide with the experimental values of Φ' for DR = -10γ. Leaving unchanged the radius a_t of the tail at a fixed index Q, we determine the theoretical boundary of the oval for a series of values of the DR-field. In Fig.2 such boundaries are drawn by solid lines.

Fig.2 shows that the experimental points of the southern boundary of aurorae borealis on the night side of the Earth are located at lower geomagnetic latitudes than the corresponding theoretical values of Φ_R', as early as for DR-field values equal to -50γ. For Q = 5 this difference attains 2°.1 at DR = -70γ. Consequently, it is difficult to explain the experimental data with a model ring current in which during a magnetic storm only the current intensity varies, while all the other parameters remain constant.

We shall now attempt to evaluate the variations of ring current parameters on the basis of the requirement that the experimental position of the oval coincide with the theoretical boundary of the closed lines of force.

To this end we shall calculate the magnetic flux carried

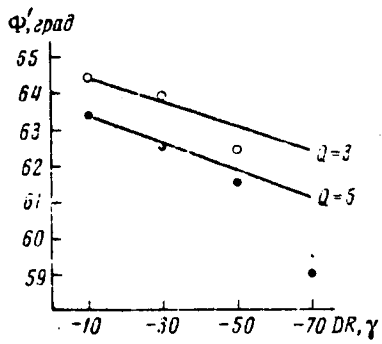

Fig.2

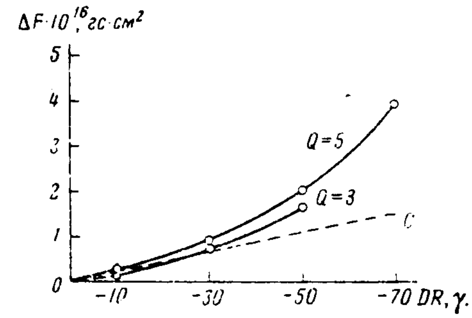

Fig.3

Fig.2 Experimental (circles) and theoretical (solid line) southern boundary of the Φ' oval of the aurorae borealis on the night side of the Earth at various values of the DR-field for the indices of magnetic activity Q equal to 3 and 5 (dark circles)

Fig.3 Dependence of magnetic flux ΔF on the ring current for index Q equal to 3 and 5 and model C (Dashed line).

away from one of the polar regions

$$F' = \frac{2\pi M}{R_E} \cos\theta_M \sin^2\theta \qquad (6')$$

at various values of the DR-field for Q equal to 3 and 5. From the obtained F' values we shall remove the background F_0' which characterizes the flux in the magnetosphere tail at a quiet magnetic field. F_0' can be obtained, for instance, by requiring the fulfilment of the $F_{-10}' = F_0' + F_{-10}^c$, at DR = $= -10\gamma$, where F_{-10}^c is the magnetic flux of model C, since at low values of DR (see Fig.2) a good agreement was obtained between theory and observations. Then the differences $\Delta F = F' - F_0'$ can be attributed to the effect of the ring current in its pure form.

As a matter of fact, on the basis of the law of magnetic flux conservation

$$F_0' + F_{cl} = \text{const} \qquad (9)$$

The ring current reduces the magnetic flux F_{cl} of the closed lines of force by ΔF_R thereby shifting the southern boundary of aurorae toward lower geomagnetic latitudes. According to (6'), an identical value of ΔF_R is added to F_0', being externally made apparent with the rise of DR, in the increase of the polar region with open lines of force.

Fig.3 shows the results of the calculations of ΔF based on observation data. For the sake of comparison the same Fig. shows the values of the magnetic flux for the previously used model C ring current.

On the other hand, according to (2) and (4) the magnetic flux from the ring current is equal to

$$\Delta F_R = \frac{2\pi M}{R_E} I_R. \qquad (2')$$

Multiplying the values of I_R shown in Table I by $2\pi M/R_E = 7.9 \cdot 10^{17}$ gs·cm^2, we obtain the values of ΔF_R for various parameters of the ring current.

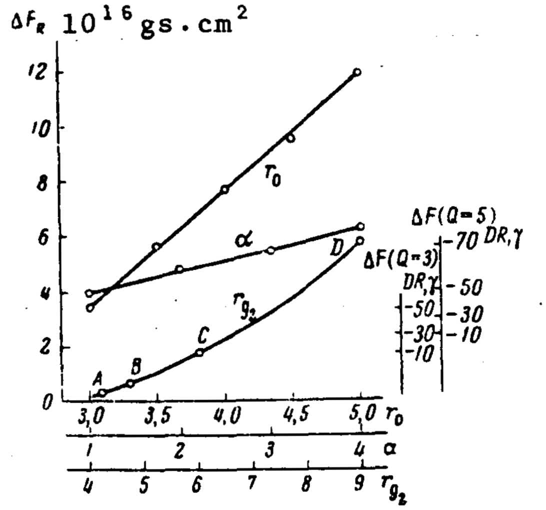

Fig.4

Dependence of magnetic flux ΔF_R on ring current parameters:
r_0 = distance to the maximum of particle density,
r_{g2} - distance to the outer boundary of particle distribution in Earth's radii and constant α.

Plotted on the right side of Fig.4 along supplementary ordinate axes are the values of ΔF taken from Fig.3, and then reduced for the sake of comparison, to the value DR = 100γ, since earlier I_R were calculated precisely for such values.

The variations in r_0 affect very strongly the magnetic flux ΔF_R. Thus, as r_0 increases from 3 to 5 R_E, ΔF_R increases by a factor of 3.5. This nature of dependence indicates rather specifically that in order to explain the experimental data it is actually necessary to adopt $r_0 \sim 3 - 3.5\ R_E$.

It was usually supposed that with increase of magnetic activity, and, consequently also of DR, the ring current at least did not drift away from the Earth [14]. For two storms in June and July 1966, the proton density maximum of the ring current was located closer to the Earth in the case of the more intense storm [12]. This is why the rise in ΔF with increase of the DR-field in Fig.3 can be explained by the withdrawal of the outer boundary of ring current protons (lower curve Fig.4) and to a certain degree by variations in pitch-angles (middle curve Fig.4). Evaluations show that for index Q equal to 3 and 5, the outer boundary from the respective distances of 6.0 and 6.7 R_E which it occupies at DR = -10γ shift by about 0.4 R_E for each subsequent increase in -10γ.

Thus, the data on the southern boundary of aurora borealis oval on the night side of the Earth make it possible to conclude that during magnetic storms the ring current is located at a distance of $\sim$ 3 - 3.5 R_E. With increase in DR the thickness of the ring current proton belt increases at the expense of the withdrawal of its outer boundary and a redistribution (reduction) of pitch-angles takes place. These conclusions yield additional information on the ring current and are not in contradiction with direct magnetic measurements on satellites and rockets in the radiation belt region.

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