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CHARACTERISTICS OF RECONNECTION EVENTS IN THE MAGNETOTAIL BASED ON AURORAL ARC MOTION IN THE IONOSPHERE

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1. Introduction

Reconnection of magnetic field lines, i.e., the process which is able to rapidly convert the magnetic energy into the thermal and kinetic plasma energy, is often described by the stationary Petschek model [*Petschek*, 1964] or its generalization for the time-dependent case [*Rijnbeek and Semenov*, 1993]. We consider the magnetic reconnection in the current sheet in the magnetotail, which, as it is supposed, is responsible for the expansion phase of the magnetospheric substorm. The reconnection begins with abrupt drop of the plasma conductivity in a local part of the current sheet (diffusion region). It is almost impossible to obtain the behavior of the plasma conductivity in the diffusion region directly from the experiment because this region is small and the probability for satellite to cross this region is negligible. Therefore, other methods are needed to estimate the plasma conductivity and some characteristics of reconnection pulse.

A sharp decrease of the conductivity gives rise to the pulse of a dissipative electric field. Under its action the charged particles accelerate and precipitate into the ionosphere where they are observed as auroral arcs moving toward the pole. It is believed [*Pudovkin et al.*, 1990] that the velocity at which arcs move northward is proportional to the reconnection rate, i.e., to the electric field in the diffusion region in the current sheet in the magnetotail. Knowing the reconnection rate as a function of time one can find how the diffusion region size and plasma conductivity vary with time from the model equation for the reconnection rate [*Rijnbeek and Semenov*, 1993].

2. Model of magnetospheric substorm

Suggested model of substorm development is based on the hypothesis about magnetic reconnection in the current sheet in the magnetospheric tail. As it is known, the expansion phase is associated with intensification of poleward motion of auroral arcs with velocities of 1-2 km/s. We suppose that each rapid poleward jump of the arc during expansive phase is caused by reconnection in the current sheet in the magnetotail in the vicinity of the neutral X-line. In the diffusion region where magnetic field is weak and electric field is rather high, the charged particles accelerate to high energies and then precipitate into the ionosphere along magnetic field lines. In course of time both reconnected magnetic flux and size of field reversal region (FRR) with accelerated and heated plasma increase, and greater and greater amount of magnetic field tubes together with frozen plasma are caught inside FRR. As a consequence, the projection of reconnection X-line in the ionosphere has to move poleward. So, it is quite reasonable to identify the auroral arc with the projection of the diffusion region in the current sheet in the magnetotail.

The electric field at the reconnection line can be estimated as follows [*Pudovkin et al.*, 1990]: for each moment of the auroral bulge development, let us consider a surface consisting of magnetic field lines which rest on the pole edge of the bulge in the ionosphere and passes through the reconnection line in the magnetotail (Figure 1). The magnetic flux through this moving contour remains zero at any of its deformations; correspondingly, the electric field circulation along this contour is also equal to zero:

$$\oint E dl = 0 .$$

With the velocity v_i of poleward auroral arc motion being known, the intensity of electric field in the diffusion region can be obtained from this equation:

$$E_m^* = k(B_i v_i + E_i) ,$$

where k is the coefficient of magnetic field line conversion, B_i is the magnetic field strength in the ionosphere, E_i is the electric field in the ionosphere estimated from plasma velocity in the ionosphere.

We can derive other parameters from the poleward moving arcs, for instance the effective potential drop across the X-line, the amount of magnetic flux released during each event and the total energy released (see Table 1).

3. Equation for the reconnection rate

Most of the models of time-varying Petschek-type magnetic reconnection use non-closed scheme where the reconnection rate is taken as a known function, and, moreover, this function, as a rule, assumed to be rather simple.
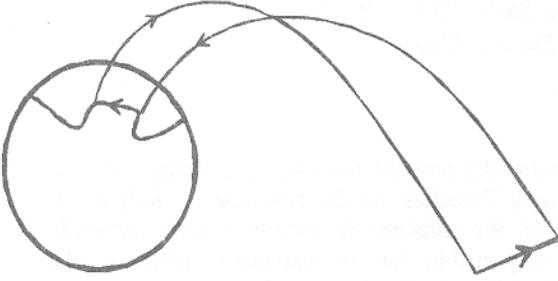

Figure 1: The contour connecting auroral bulge and reconnection line in the magnetotail.
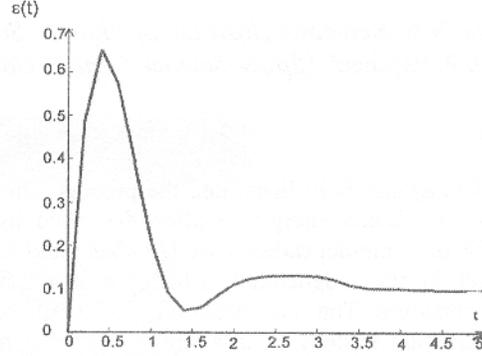
Figure 2: The model reconnection rate $\varepsilon(t)$ as a function of time.

At the same time, according to experimental data, the pulse of reconnection is strongly asymmetrical: the electric field along the reconnection line, first, quickly increases and then slowly decreases. We present a model, which can describe this behavior of the reconnection rate.

Let us consider a two-dimensional configuration in which a thin current sheet (tangential discontinuity) separates two plasma regions with homogeneous anti parallel magnetic fields $\pm \vec{B}_0$. Reconnection starts with a decrease of plasma conductivity inside the diffusion region, and, thus, a dissipative electric field $E^* = j/\sigma$ has to appear here. Then the electric field is transported by MHD waves to the current sheet at large, acts there on the source of magnetic field $\vec{j}$, so that $(\vec{E}\vec{j}) > 0$, and it means that the magnetic energy is converted into the kinetic and internal energy of the plasma. Simultaneously, the disturbed part of the current sheet decays into two pairs of slow shocks, at which plasma is accelerated up to the Alfvén velocity $v_a = B_0/\sqrt{\mu_0\rho_0}$ and heated [*Pudovkin et al.*, 1990; *Rijnbeek and Semenov*, 1993]. Thus, the electric field generated in the small diffusion region due to a dissipative process is transported by MHD waves to the current sheet and acts there as a convective electric field.

The reconnection process is strongly self-consistent: dissipative electric field initiates reconnection, but, on the other hand, the magnetic field strength varies near the diffusion region in course of reconnection, which leads to changes in the current density and electric field in the diffusion region. We suggest a simple model, which can take into account this self-consistency [*Rijnbeek and Semenov*, 1993].

To derive the relationship between the plasma conductivity $\sigma(t)$ and reconnection rate $\varepsilon(t) = E^*(t)/E_a$, where $E_a = v_a B_0$, we consider the diffusion region with length of $2l$ along the current sheet and thickness of $2d$. We restrict ourselves to the case of weak reconnection when $\varepsilon \ll 1$.

We can estimate the dissipative electric field as follows: $E^*(t) = \dfrac{j}{\sigma(t)} = \dfrac{1}{\mu_0\sigma(t)} \cdot \dfrac{\Delta B_x}{2d}$, where $\Delta B_x = 2(B_0 + B_x^{(1)})$ is the jump

of the magnetic field across the diffusion region. First-order term $B_x^{(1)}(t,x,y)$ can be found from the solution of time-varying reconnection problem and thus we can obtain the equation for the reconnection rate [*Rijnbeek and Semenov*, 1993]:

$$\varepsilon(t) = \frac{1}{re_m}\left(1 - \frac{2}{\pi}\varepsilon(t - \Delta) - \frac{4}{\pi}\int_0^{t-\Delta}\frac{\varepsilon(\tau)}{t - \tau}d\tau\right),$$

where $re_m = \mu_0\sigma(t)dv_{drift} \approx 1$ is the magnetic Reynolds number calculated with respect to the half width of the diffusion region d, Δ is the half length of diffusion region divided by the Alfvén velocity, i. e., varied diffusion time $t_D(t)$. Figure 2 shows the result of this calculation. To calculate the varied diffusion time the equation is rearranged. Then the behavior of the plasma conductivity in the diffusion region during reconnection event can be obtained from: $\sigma(t) = 1/(\mu_0 t_D(t)v_{drift}^2)$.
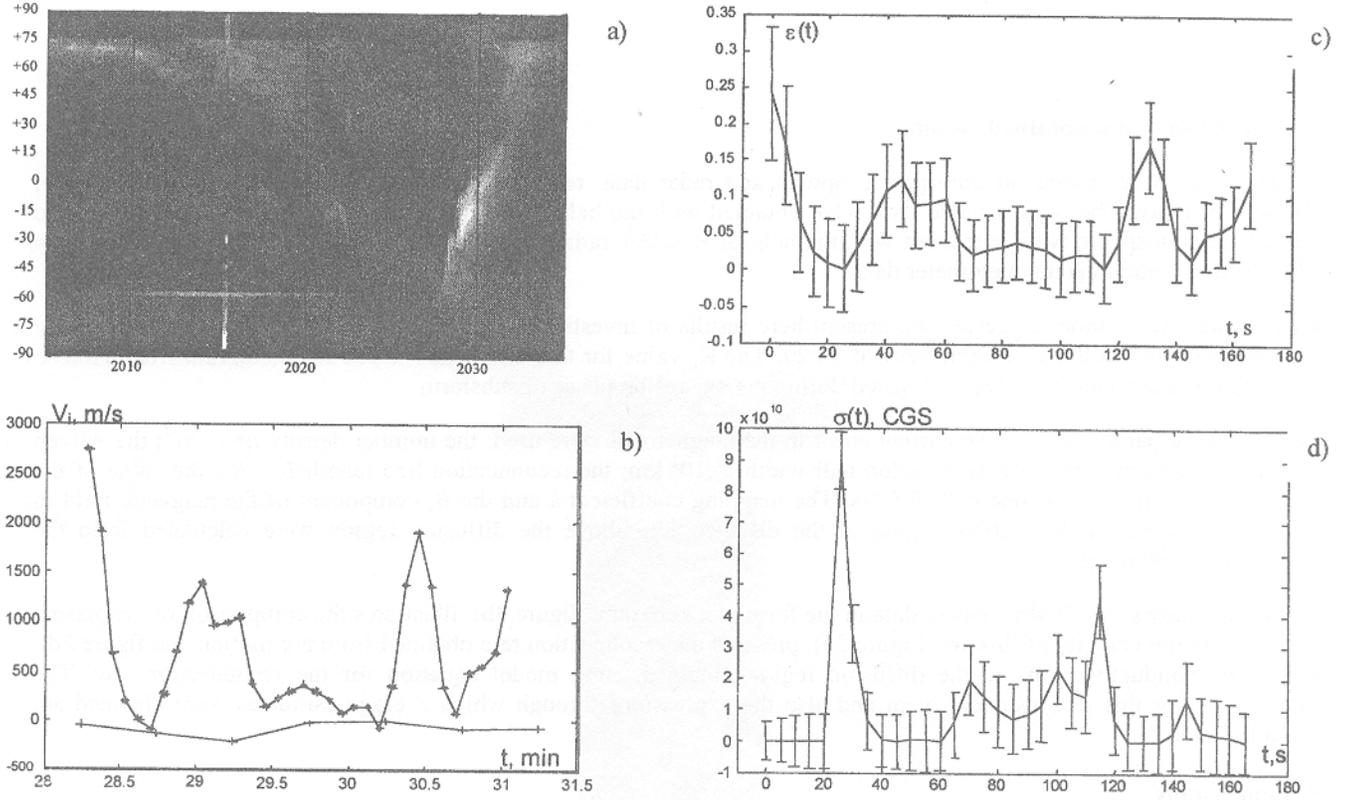
Figure 3: a)- all-sky optical data in the form of a keogram for the event occurred on the 7th March 1991 at 20:29 UT, b)- the arc velocity (*) and plasma velocity (+), m/s, c)- reconnection rate for this event, d)- plasma conductivity inside the diffusion region, CGS

Table 1: Parameters of an elementary reconnection event in the magnetotail.

Parameters	Designations	Obtained results
		Tromso, 20:29 UT
Geographical coordinates of the initial point	φ, λ	$\varphi = 68,29$ N, $\lambda = 19.22$ E
Coefficient of magnetic field line conversion	k	1/55
B_x-component of magnetic field in the magnetosphere, nT	B_m	28
Mean velocity of the poleward arc motion, m/s	$\overline{v}_i$	770
Average strength of dissipative electric field in the diffusion region, mV/m	$\overline{E}_m^* = k\left(\overline{v}_i B_i + \overline{E}_i\right)$	0,7
Alfven electric field, mV/m	$E_a = v_a B_m$	11
Average reconnection rate	$\overline{\varepsilon} = \overline{E}_m^* / E_a$	0,06
Average plasma conductivity in the diffusion region, CGS	$\overline{\sigma} = 2B_m / \mu_0 \overline{E}_m^* d$	5×10^6
Average drift velocity, km/s	$\overline{v}_{drift} = \overline{E}_m^* / B_m$	26
Average diffusion time, s	$\overline{t}_D = 1 / \mu_0 \overline{\sigma} \, \overline{v}_{drift}^2$	20
Effective potential difference across reconnection line, kV	$\Delta\varphi = \overline{E}_m^* L_t$	22
Reconnected magnetic flux, Mx	$F_b = L_i \int_0^t E_m^*(t) d\tau$	3×10^{14}
Released magnetic energy, erg	$W = \dfrac{\rho v_a^3}{B_m} \int_0^t F_b(\tau) d\tau$	$1,2 \times 10^{19}$
Minimum value of plasma conductivity in the diffusion region, CGS	σ_{min}	$1,6 \times 10^6$

4. Observations and obtained results

Investigations were based on ionospheric optical and radar data, recorded at the EISCAT facility near Tromsø, in northern Norway. The optical video data were obtained with the help of all-sky camera, plasma velocity and electric field in the ionosphere were measured with the help of EISCAT radar, magnetic field behavior in the ionosphere was taken from Scandinavia magnetometer data.

To illustrate the method suggested we present here results of investigation for one event of the poleward auroral arc motion occurring on the 7th March 1991 at 20:29. The K_p value for this time was 4[+]. The magnetogram from Tromsø shows that this reconnection event occurred during the expansion phase of substorm.

The following parameters for the current sheet in the magnetotail were used: the number density $n=1$ cm^{-1}; the Alfvén velocity v_a=400km/s; the diffusion region half width $d=10^3$ km; the reconnection line length $L_i=5R_E$; the value of the magnetic field in the ionosphere B_i=0.5 Gs. The mapping coefficient k and the B_x-component of the magnetic field in the magnetosphere in the inflow region at the distance $1R_E$ above the diffusion region were calculated from the Tsyganenko T89 model.

Figure 3a). shows the all-sky camera data in the form of a keogram. Figure 3b). illustrates the comparison of the plasma velocity and the velocity of this arc. Figure 3c). presents the reconnection rate obtained from arc motion and figure 3d). shows the conductivity inside the diffusion region obtained using model equation for the reconnection rate. The calculations for this reconnection event and also the expressions through which average estimates were obtained are listed in Table 1.

5. Conclusions

We present here a method, which enabled us to measure the reconnection rate from the motion of auroral arcs and from this calculate the conductivity inside the diffusion region. The event discussed is a typical case of reconnection events in the magnetotail during expansive phase of substorm and corresponding to substorm auroral arc motion in the ionosphere, so we summarize the results as following:

1). Breakup starts with the drop of plasma conductivity to the value of order of 10^4-10^6 CGS which is 12-10 orders less than its classical Spitzer value and which is slightly more than Bohm conductivity. It is suggested that reconnection is triggered by an anomalous resistivity.

2). Reconnection events occur generally at the expansion phase of substorm.

3). In the breakup events considered, the reconnection operates in the impulsive regime associated with the short-term (1-4 min) drop of conductivity in the diffusion region in the current sheet in the magnetotail. The impulsive nature of reconnection is responsible for the impulsive nature of substorm (which confirms the earlier findings [*Sergeev et al.*, 1987]).

4). Diffusion time varies from 10 to 30 seconds, while the overall duration of the reconnection pulse is 5-15 t_D. Magnetospheric electric field in the diffusion region turns out to be 0.5-3 mV/m, effective potential difference across the reconnection line is 20-100 kV.

5). The typical values of the reconnected magnetic flux of the order of 10^{14}-10^{15} Mx and released magnetic energy of 10^{19}-10^{20} erg indicate that during several tens of elementary activations often observed during a substorm, the entire magnetic flux accumulated during the initial substorm phase can be reconnected (10^{16}-10^{17} Mx) and the overall substorm energy can be obtained (10^{21}-10^{22} erg).

References

Petschek, H. E., Magnetic field annihilation, *NASA Spec. Publ., SP-50,* 425, 1964.

Pudovkin, M. I., Semenov, V. S., Kornilova, T. A., Kozelova, T. V., The development of a magnetospheric substorm: theory and experiment, *Researches in geomagnetism, aeronomy and solar physics,* Irkutsk, V.89, P. 5-57, 1990.

Rijnbeek, R. P., and Semenov V. S., Features of a Petschek-type reconnection model, *Trends in Geophysics Res.,* 2, 247-267, 1993.

Sergeev, V. A., Semenov, V. S., and Sidneva, M. V., Impulsive reconnection during substorm expansion, *Planet. Space Sci.,* 35, 1199-1212, 1987.