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A New Mechanism for Interpreting the Motion of Auroral Arcs in the Nightside Ionosphere

V. S. Semenov and Y. V. Bogdanova

Institute of Physics, State University, St. Petersburg, Russia

R. P. Rijnbeek and M. J. Buchan

Space Science Centre, University of Sussex, UK

Abstract. A new mechanism is proposed for predicting and interpreting the motion of auroral arcs observed in the nightside ionosphere during the expansion phase of a substorm. This mechanism is centred on the idea that such arcs act as visible manifestations of the arrival of earthward-propagating shock waves in the near-Earth magnetosphere. These shock waves are generated at a near-Earth X-line, and propagate at the local Alfvén speed. Because of the non-uniform nature of the magnetised plasma in the magnetotail, dispersion results in a change in the shape of the wave fronts as the shocks propagate towards the ionosphere. Theoretical analysis shows that a variety of arc motions can occur as a result of this dispersion, depending on factors such as the reconnection rate, the location of the reconnection site, and gradients in the magnetic field strength and plasma density.

Introduction

The stunning light show observed in the upper polar atmosphere, known as the aurora, is a dramatic manifestation of the complex sequence of interactions which occur between the solar wind, magnetosphere, and ionosphere [*Bone*, 1996]. The study of this phenomenon provides, potentially, an empirical means of monitoring processes such as reconnection [*Hones*, 1984], but there are still many unanswered questions relating to the formation, structure and dynamics of auroral arcs. Of particular interest to us is the need to explain the auroral breakup phenomenon, i.e., the intensification and rapid poleward jump of the auroral arc which marks the poleward boundary of the nightside auroral oval at substorm onset. Recent observations have revealed that subsequently new arcs appear northward of the onset arc, with a reduced poleward velocity [*Kornilova et al.*, 1996]. This stage also marks the (re)appearance of equatorward moving arcs.

In this article we present a new mechanism for interpreting the observed dynamic behaviour of the aurora during the expansion phase of a substorm. This phase of the substorm can be explained in terms of the onset and subsequent enhancement of magnetotail reconnection, often associated with the appearance of a new reconnection site (X-line) close to Earth ($\sim 20\ R_E$). The new mechanism builds on the hypothesis that magnetotail reconnection is central to the development of a substorm, and that the auroral breakup observed at substorm onset is associated with processes which occur in the vicinity of a near-Earth X-line. It combines the main ingredients of Petschek-type reconnection models [*Petschek*, 1964; *Semenov and Vasiliev*, 1985] – the MHD shock waves which have been observed in spacecraft data and simulations [*Feldman et al.*, 1984; *Scholer*, 1991], and their associated field-aligned currents – with those of auroral arc theories [*Borovsky*, 1993] – the upward field-aligned currents associated with electrons precipitating into the ionosphere, and near-Earth acceleration mechanisms such as double layers to achieve the required energisation.

The proposal that the auroral breakup phenomenon can be interpreted as the manifestation of magnetotail reconnection is not new [*Hill and Reiff*, 1980; *Pudovkin et al.*, 1990; *Rostoker*, 1991; *Atkinson*, 1992]. What is new is the proposition that the location and motion of auroral arcs observed during the expansion phase of a substorm corresponds to the ionospheric manifestation of upward field-aligned currents induced by earthward-propagating shock waves, which are generated by a bursty, Petschek-type reconnection process in the magnetotail current sheet.

The next section contains the body of this article; here we introduce the new mechanism and analyze its main features using a simplified model of the current sheet geometry in the magnetotail. We show that the auroral manifestation of magnetotail reconnection includes poleward and equatorward moving arcs, as well as arcs which show a combination of these types of motion. Hence, the new mechanism predicts a richer variety of arc motions and morphology than is commonly supposed.

A New Mechanism for Interpreting Auroral Dynamics

Figure 1 shows a schematic illustrating the new mechanism for interpreting the motion of auroral arcs during a magnetospheric substorm. We suppose that reconnection is initiated along a near-Earth X-line at the onset of a substorm, as the result of an abrupt drop of the plasma conductivity inside the diffusion region. This decrease in the conductivity is accompanied by the appearance of a reconnection electric field along the X-line, which is dissipative in origin. In the process, pairs of nonlinear shock waves are generated which propagate earthward and tailward along the magnetotail current sheet. Plasma convecting in towards the current sheet is accelerated across the wave fronts, thus establishing an outflow region of reconnected plasma.

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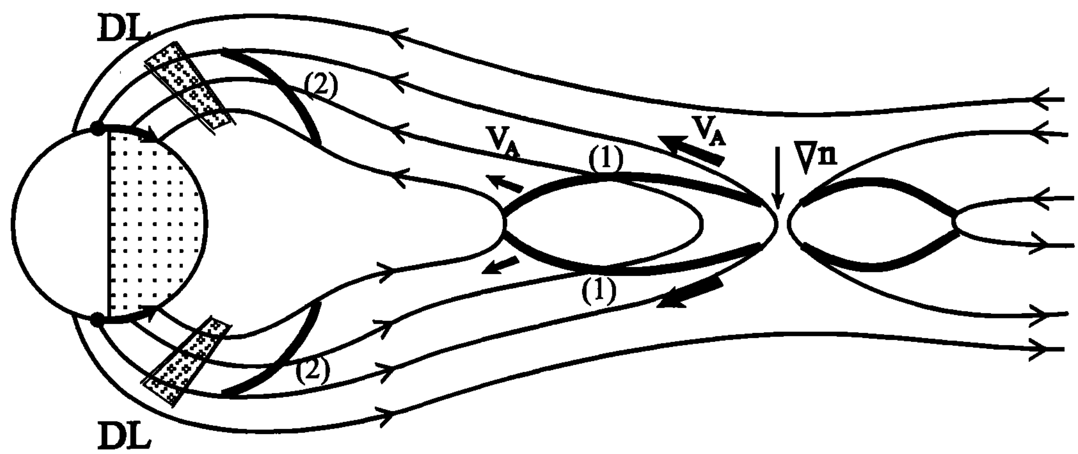

Figure 1. Schematic illustrating the new mechanism for predicting and interpreting the location and motion of auroral arcs during the substorm expansion phase. Reconnection at a near-Earth X-line generates pairs of shock waves propagating in opposite directions. The earthward-propagating shocks are shown at two different times, labelled (1) and (2), respectively. In the near-Earth magnetosphere the shocks and associated field-aligned currents trigger double layers, labelled DL, which accelerate charged particles towards the ionosphere and upper atmosphere. The precipitating particles then give rise to visible emissions in the form of auroral arcs, the motion of which reflects the arrival time of different parts of the shock fronts. In this particular case, equatorward moving arcs are generated, as indicated by the bold arrows along the surface of the Earth.

With time, both the volume of reconnected plasma, as indicated by the size of the outflow region, and the amount of reconnected flux, as indicated by the poleward displacement of the separatrix (the magnetic field line marking the boundary between the reconnected and unreconnected field lines), increase. Once reconnection ceases, the outflow region and the separatrices detach from the inactive reconnection site, and the current sheet is re-established.

The characteristic speed of propagation of the shock waves is the local Alfvén speed

$$V_A = \frac{B}{\sqrt{\mu_0 \rho}}, \tag{1}$$

where B is the local magnetic field strength and ρ is the mass density. If, as we suggest here, it is the arrival of the earthward-propagating shock waves in the near-Earth magnetosphere which eventually triggers the appearance of auroral arcs in the nightside ionosphere, then in order to interpret the motion of these arcs we have to take into account the finite propagation speed of the shock waves as they travel from the magnetotail reconnection site towards the ionosphere. In particular, the shape of the shock fronts will change due to the non-uniform nature of the plasma medium through which the waves propagate, and this will in turn affect the location and dynamics of the observed auroral arcs. This is illustrated in Figure 1, which shows the location and shape of the earthward-propagating shocks bounding the outflow region at two different times: just after a pulse of reconnection, labelled (1), and some time later as they approach the ionosphere, labelled (2).

Across the shock fronts, plasma is accelerated to the upstream Alfvén speed, which corresponds to energies of order 1 keV for the protons and 10 eV for electrons. This is not sufficient to explain the appearance of the bright arcs observed during substorms, which requires energies of order $1-10$ keV for the precipitating particles, and so we need to invoke an additional acceleration mechanism; we do this in the form of a double layer, labelled DL in Figure 1. This is a region in the near-Earth magnetosphere, at an altitude of say $1-2$ R_E along the auroral field lines, where a localised breakdown of the frozen-in condition gives rise to the appearance of parallel electric fields. We assume, furthermore, that it is the arrival of the incoming shock waves and the associated field-aligned currents which in some way triggers the appearance of the double layer, and hence the precipitation of energetic charged particles into the ionosphere. Thus, the location and motion of auroral arcs, as indicated by the thick bold arrows along the Earth's surface in Figure 1, reflect the different times of arrival of different portions of the shock front in the near-Earth magnetosphere. Our suggested mechanism therefore combines a generator/source mechanism in the form of a Petschek-type reconnection process along a near-Earth X-line to explain the location and motion of the bright auroral arcs observed during the expansion phase of a substorm, with a near-Earth acceleration mechanism in the form of a double layer to produce the required energisation of the charged particles precipitating into the ionosphere.

To investigate the consequences of this mechanism in more detail, we consider a simplified two-dimensional current sheet geometry, as illustrated in Figure 2. The central current sheet is denoted by the hatched region, and we have introduced a Cartesian coordinate system in which the positive $x-$axis is tangential to the current sheet and points earthward (from right to left in the figure), and the positive $z-$axis is perpendicular to the current sheet and points northward (upward in the figure); this facilitates comparison with observations plotted in magnetospheric coordinates.

As mentioned before, the shock fronts evolve as they travel away from the reconnection site. This evolution depends on the nature of the non-uniform magnetised plasma medium through which the shocks propagate. In particular,

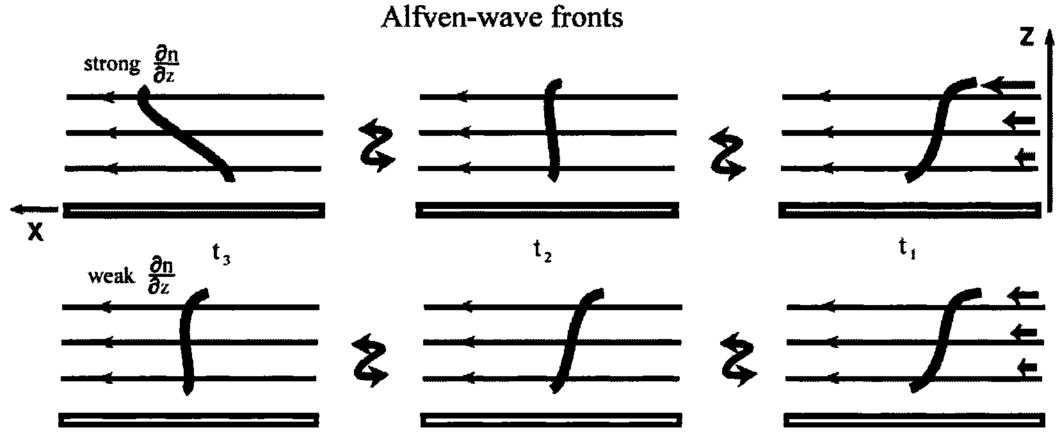

Figure 2. Simplified representation of the magnetotail current sheet geometry. The current sheet is indicated by the hatched horizontal bars, and the thin arrowed lines show the magnetic field lines in the northern lobe. The bold curvy lines show the shape of the wave front of the shocks generated at a near-Earth X-line (to the right of this figure) as they propagate towards the Earth (to the left). Snapshots are shown at three different times, labelled t_1, t_2, and t_3, to illustrate the effects of dispersion as the shocks propagate earthward. Two sequences are shown; the top sequence corresponds to the case of a strong gradient in the plasma density perpendicular to the current sheet, and the bottom one to a weak gradient.

since the shock waves propagate at the local Alfvén speed (equation (1)), we may anticipate that gradients in the magnetic field and the plasma density lead to dispersion, and hence a change in the shape of the shock fronts as different plasma conditions are sampled, as illustrated in Figure 2. This dispersion in turn will affect and determine the motion of auroral arcs in the nightside ionosphere if, as we suggest, the arcs are the visual manifestation of the arrival in the near-Earth magnetosphere of reconnection-generated shock waves.

To put these qualitative arguments on a firmer footing, we now apply some simple theoretical arguments. Application of Faraday's law shows that the amount of reconnected magnetic flux per unit length of the X-line, $\phi(t)$, can be written in terms of the reconnection electric field $E^*(t)$:

$$\phi(t) = \int_0^t E^*(\tau)\, d\tau, \tag{2}$$

where t is the time measured from the onset of reconnection. The reconnected flux can also be defined in terms of the magnetic field according to the formula

$$\phi(z) = \int_0^z B_x(z')\, dz', \tag{3}$$

where B_x is the component of the magnetic field tangential to the current sheet. This equation can also be written in differential form as

$$B_x = \frac{d\phi}{dz}. \tag{4}$$

Furthermore, since for an initially static configuration the pressure gradient force is balanced by the ampere force, the plasma pressure (and hence the density) is constant along the field lines. Hence, for our purposes it is the density gradient perpendicular to the current sheet which is the important factor affecting the Alfvén velocity (1).

As reconnection proceeds, we can imagine magnetic field lines convecting in from the plasma sheet and tail lobes towards the central current sheet. Each field line can be labelled uniquely by specifying the appropriate value of z, the distance it has to convect in towards the current sheet as measured at the time of reconnection onset, and t_{rec}, the time at which the field line reconnects. Combining equations (2) and (3), we can express the time t_{rec} as a function of z, the coordinate perpendicular to the current sheet: $t_{rec} = t_{rec}(\phi(z)) = t_{rec}(z)$. The location and shape of the shock fronts can therefore be derived from an equation of the form

$$x(z,t) = V_A(z)\,[t - t_{rec}(z)] \tag{5}$$

where $t_{rec}(z)$ is the time elapsed since the onset of reconnection for a field line marked by the value of z. To examine how the dispersion of the shocks affects the corresponding motion of auroral arcs, we set $x(z,t)$ equal to a constant value, corresponding to the distance between the X-line and its near-Earth projection, and then differentiate the above expression (5) to obtain the following equation for the north-south component of the arc velocity, U_{arc}:

$$U_{arc} = \frac{dz}{dt} = \left(\frac{dt_{rec}}{dz} - \frac{1}{V_A}\frac{dV_A}{dz}\Delta t\right)^{-1}, \tag{6}$$

where $\Delta t = t - t_{rec}$ is the time it takes to travel from the X-line to the near-Earth magnetosphere. Using equations (2) and (4) together with the chain rule for differentiation we obtain

$$\frac{dt_{rec}}{dz} = \frac{dt_{rec}}{d\phi}\frac{d\phi}{dz} = \frac{B_x}{E^*}. \tag{7}$$

Substituting into equation (6) and with some rearrangement we finally obtain the following rather simple expression for the arc motion:

$$U_{arc} = V_A\left(\frac{1}{\varepsilon} - \frac{1}{\chi}\right)^{-1}, \tag{8}$$

where we have introduced two dimensionless parameters defined as

$$\varepsilon \equiv \frac{E^*}{V_A B_x} \qquad \chi \equiv \frac{\left(\frac{1}{V_A}\frac{dV_A}{dz}\right)^{-1}}{(V_A\Delta t)} = \frac{\Delta z}{\Delta x}. \tag{9}$$

Here ε is the reconnection rate, and χ is a parameter which is the ratio of the scale length of the gradient in the Alfvén velocity perpendicular to the current sheet, Δz, and the distance the shock has to travel from the magnetotail to the near-Earth magnetosphere, Δx. Note that equation (8) overestimates the arc velocity; in practice we need to introduce a correction factor to account for the convergence of the geomagnetic field lines into the ionosphere.

To interpret the physical significance of the result we have obtained, we consider two limiting cases:

$$\varepsilon \ll \chi \implies U_{arc} \approx \varepsilon V_A \quad (10)$$

$$\varepsilon \gg \chi \implies U_{arc} \approx -\chi V_A. \quad (11)$$

In the former case, the arc has a poleward motion which is proportional to the reconnection rate; this is most likely to occur when the reconnection rate is weak, the gradients in the magnetic field and plasma density, and hence the Alfvén velocity, are weak, and the X-line is situated close to Earth. For the converse case, when the second inequality applies, the arc moves equatorward, as illustrated in Figure 1. In general, the arc may display a combination of both types of motion, as illustrated in Figure 2; in this case we could see more complicated arc structures such as a 'double' or 'C-shaped' one in which the emission originates at a point from which one branch moves poleward and the other equatorward. Further analysis is in progress to examine the spectrum of possible signatures, and compare the theoretical predictions with actual observations.

Summary

We have presented a new mechanism for interpreting and predicting the motion of auroral arcs in the nightside ionosphere, based on the hypothesis that these arcs are the manifestation of earthward-propagating shock waves generated by reconnection in the magnetotail current sheet. Simple theoretical arguments, based on a simplified representation of the magnetotail current sheet geometry, reveal that:

- Magnetotail reconnection can give rise to poleward moving arcs, equatorward moving arcs, and/or arcs which combine both types of motion.
- The dynamics of auroral arcs is strongly dependent on three parameters: the gradient of the Alfvén speed in the magnetotail, the position of the X-line, and the behaviour of the reconnection rate.
- Poleward moving arcs appear preferentially when the reconnection-generated shocks arrive quickly in the near-Earth magnetosphere, they sample weak gradients in the magnetic field and plasma density, and hence the Alfvén velocity, and the reconnection electric field is weak. Conversely, the equatorward moving arcs occur preferentially when the shocks take a long time to arrive, the gradients are strong, and the reconnection electric field is strong.

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Vladimir S. Semenov and Yulia V. Bogdanova, Institute of Physics, State University, St. Petersburg, 198904 Russia. (e-mail: sem@snoopy.phys.spbu.ru; julia@geo.phys.spbu.ru)

Richard P. Rijnbeek and Maria J. Buchan, Space Science Centre, School of CPES, University of Sussex, Brighton BN1 9QH, UK. (e-mail: R.P.Rijnbeek@sussex.ac.uk; M.J.Buchan@ sussex.ac.uk)

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