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Auroral fading in ionosphere-magnetosphere coupling model: Implications for possible mechanisms

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Abstract. Sudden fading of the growth phase auroral arc and precipitation is sometimes observed just prior to substorm expansive phase onset. We can see a very similar phenomenon in a numerical ionosphere-magnetosphere coupling model. In the numerical simulation, the fading occurs because the region of hot and dense magnetospheric plasma moves towards the Earth. At the same time, the plasma that maps to the poleward part of the fading area is cooled, which reduces precipitation there. The hot and dense plasma near geostationary orbit continues to precipitate, but to a lesser extent because it resides in a more dipolar field. Thus the fading phenomenon appears to to occur because the hot and dense plasma is temporarily "hidden" from the ionosphere. A few minutes later it moves tailward which causes the auroral brightening.

Introduction

The substorm growth phase is a phase of enhanced energy input into the magnetosphere. Usually the slow, linear evolution phase lasts about an hour during which the auroral arcs drift equatorward and the electrojets slowly enhance. However, in some substorms, the linear evolution is disturbed during the last few minutes of the growth phase: the auroral arcs fade and the electrojets become weaker. This is accompanied by a decrease in the upward field-aligned current and a decrease in the hard (tens of keV) precipitation (e.g., *Pellinen and Heikkila,* 1984, *Kauristie et al.,* this issue).

Previously the auroral fading and the associated decrease in other activity parameters have been reported in connection with several events, but the cause and the spatial extent have remained unclear. Using a magnetosphere-ionosphere coupling model we show that such a fading possibly forms due to magnetospheric processes, and can extend over a large portion of the auroral ionosphere.

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Modeling

Our semiglobal ionosphere-magnetosphere coupling model GUMICS ("Grand Unified Magnetosphere-Ionosphere Coupling Simulation") consists of three main parts: the ionosphere, the magnetosphere, and the coupling field-aligned currents. The model is a substantial extension of an earlier model by *Janhunen and Huuskonen* [1992, 1993]: The magnetosphere is modelled using 3D MHD equations. Spherical coordinates are used in the ionospheric plane, and a more realistic field line mapping is employed in the force-free region.

The ionosphere in the GUMICS model is modelled as a two-dimensional (2D) medium with varying height-integrated Pedersen and Hall conductivities. The computational cycle of one time step starts by inputting the magnetospheric FAC to the ionosphere. The ionospheric potential Φ_i is computed by solving the current continuity equation,

$$-\nabla \cdot (\mathbf{\Sigma} \cdot \nabla \Phi_i) = j_{\|}^{(i)}, \tag{1}$$

where $\mathbf{\Sigma}$ is the height–integrated conductivity tensor and $j_{\|}^{(i)}$ is the FAC at ionospheric level (positive downward).

The magnetosphere–ionosphere coupling is modeled by assuming that a linear relationship of the form $j_{\|}^{(i)} = K(\Phi_m - \Phi_i)$ exists between the FAC and the magnetosphere–ionosphere potential drop, where K is the Lyons-Evans-Lundin constant [*Fridman and Lemaire,* 1980]. Since $j_{\|}^{(i)}$ and Φ_i are known at this stage, Φ_m can easily be computed. This magnetospheric potential is mapped along *Tsyganenko* [1989] (T-89) model field lines to the plane $x = -6$, where x, y, z are the GSM coordinates in units of Earth radii.

The magnetosphere is represented by a rectangular simulation box with slightly modified MHD equations inside [e.g., *Matsumoto and Sato,* 1985]. The dimensions of the box are $-20 < x < -6, -6 < y < 6, 0 \leq z < 5$. The potential Φ_m at the earthward face at $x = -6$ is used to determine the perpendicular velocity $v_\perp = \mathbf{B} \times \nabla \Phi_m / B^2$, which is then used as a boundary condition. The MHD equations are then integrated one step forward in time ($\Delta t = 0.1$ s), after which the FAC is computed at the earthward face from its MHD definition, $j_\| = \hat{\mathbf{b}} \cdot \nabla \times \mathbf{B}$, where $\hat{\mathbf{b}}$ is the unit vector in the direction of $\mathbf{B}$. This FAC is mapped to the ionosphere.

"Soft" boundary conditions are used in the MHD box: after each time step, the imposed boundary function is mixed with the solution using a mixing factor which is finite at the boundaries and goes rapidly to zero in the central regions. This helps avoid some numerical problems at the cost of having finite transition layers of unphysical grid points near the boundaries. The spatial boundary conditions are the same as the initial condition for all dynamical variables ρ, p, $\mathbf{v}$ and $\mathbf{B}$, and hemispherical symmetry at $z = 0$ is assumed.

The generation of initial conditions for the MHD box proceeds as follows. The magnetic field is computed from the T-89 model. The pressure is obtained by satisfying $\mathbf{j}\times\mathbf{B} = \nabla p$ as closely as possible. The velocity is zeroed and the density ρ is obtained assuming adiabaticity with $\gamma = 3/2$.

Because the plasma density and temperature at the earthward face $x = -6$ is known from the MHD variables, it is possible to compute the precipitating electron flux, if the filling rate of the loss cone after a single bounce period is known. Out model for the loss cone filling rate is very small (0.02) at $x = -6$ and grows close to unity at the tailward end. The filling rate model has been chosen to give reasonable ionospheric conductivities. After computing the precipitating electron flux, the ionospheric production rate q is computed in a 3D grid. The electron density n is obtained by integrating the equation $\partial n/\partial t = q - \alpha n^2$ one step forward in time, where α is the recombination constant. Finally, the Pedersen and Hall conductances Σ_P and Σ_H are obtained from n by height integration and modelled profiles for the collision frequencies.

The ionospheric end of the simulation box is rectangular in magnetic dipole coordinate latitude and longitude over Scandinavia and northern Finland covering geomagnetic latitudes 62° - 74° and longitudes $-50°$ - $+50°$. We redefine zero magnetic longitude to coincide with the midnight meridian; this is possible as we assume zero dipole tilt angle. The auroral luminosity can be inferred from the simulation in several different ways; one can consider the height-integrated Hall or Pedersen conductivity or the ionization production rate. The top panel of Figure 1 shows the height-integrated Pedersen conductivity after 42 minutes of simulation, during a relatively quiet epoch. The different methods to estimate auroral luminosity lead to qualitatively similar results for the case studied here. Notice, however, that the resolution of the model is not sufficient for representing individual auroral arcs; only estimates for average auroral brightness can be given.

Figure 1

Results

To illustrate the simulation results, we have plotted the height-integrated Pedersen conductivity at five moments of time. (Figure 1). Figure 2 presents the magnetic disturbances as "magnetograms" computed along the midnight meridian. The latitudes are chosen to correspond to the IMAGE magnetometer network stations

[*Viljanen*, 1995]. Figure 3 gives the Hall conductivity as a function of time and latitude in a color-density plot. The yellow and red areas give the location of the auroral oval during the simulation run.

Figure 2

The initial state is allowed to develop for one hour without a cross-tail electric field to reduce transient effects associated with a slight force imbalance in initial state. After this, at $t = 0$, the velocity boundary condition is changed to model earthward plasma convection, corresponding to an average 0.3 mV m^{-1} cross-tail electric field throughout the MHD simulation box.

The time development during the one-hour simulation period can be summarized as follows. Switching on of the electric field yields rather soon an equatorward motion of the auroral oval. At the same time, the oval becomes thin in the north-south direction. At $t = 7$ min a small auroral breakup occurs in the thinned oval that results in brightening of the oval as well as northwest motion of the auroras. At $t = 15$ min the system arranges itself in a double oval configuration. The northern oval is a trace of relatively dense plasma that was injected tailward during the breakup. The southern oval is, on the other hand, mainly caused by the high temperature of the plasma closer to the Earth ($x > -8$). The double oval situation remains remarkably stationary for about fifteen minutes. At $t = 35$ min the northern oval starts an accelerating equatorward motion, which results in a new fading of the auroral distribution followed by a new breakup at $t = 45$ min. In Figure 3 we can see that during the double oval situation the northern edge of the northmost oval moves southward at about 5 km/min. Just before the fading the northern boundary moves ten times faster, 50 km/min. The southern boundary of the northmost oval, whenever well defined, moves at about 12 km/min on the average. The second breakup is stronger than the first one. The two breakups can be clearly seen also in the simulated ground magnetograms (Figure 2).

Figure 3

Both breakups (at 7 min and 45 min) are preceded by a period of fading of the auroral distribution (Figure 1) and decrease in the auroral electrojet intensity (Figure 2). Both breakups are rather similar as far as fading is concerned, except that the second fading is more complete. Here we concentrate on the second event. The bottom panels of Figure 1 show the height-integrated Pedersen conductivity as a density (intensity) plot at one minute intervals just before and at the second fading and activation. The large panel ($t = 42$ min) shows the situation about two minutes before fading starts.

In the course of fading, a nonconducting (dark) region resides north of the southward moving oval. The dark area expands and partly overlaps the oval, and at the same time the northern edge of the oval becomes sharper. At $t = 42$ min, before the fading, the double oval situation no longer exists (see also Figure 3), and the northern oval has joined the southern one. The oval moves southward. In the next panel (t = 43 min) the southward motion continues and the fading starts. The fading seems to occur because a nonconducting (dark) area north of the oval expands southward at a higher speed than the oval. At t = 44 min the fading has reached its peak; the oval is very thin and weak in this panel. In the next frame the breakup is seen as a brightening of the southern edge of the oval that rapidly expands eastward and westward. Although the brightening starts at the southern edge, it quickly proceeds also northward, which is clearly visible in the last frame (t =46 min).

Discussion

The ionosphere-magnetosphere coupling model presented here seems capable of producing substorm activation like events complete with growth phase, breakup, and expansion phase. The auroral fading is colocated with a weakening of the westward electrojet prior to the breakup, similar to that reported most recently by *Kauristie et al.* (this issue).

The auroral fading in the simulation occurs when the hot and dense plasma in the magnetotail moves closer to the Earth (southward motion of the oval). At the same time, plasma farther down the tail ($x < -12$) becomes more dilute and is also cooled. On near-Earth dipolar field lines ($x > -8$), the possibility that the plasma population will cause significant precipitation is smaller, because of lesser pitch angle diffusion. Thus the reason for fading in our simulation appears to be that the plasma that would have sufficiently high density and temperature for significant precipitation is so close to the Earth that the precipitation is effectively blocked because there are no efficient pitch angle scattering processes.

The auroral brightening after the breakup is a manifestation of a tailward motion of hot and dense plasma. Notice that this tailward motion is opposite to the average earthward drift caused by the imposed electric field. The plasma seems to "bounce back" towards the tail at this stage. One scenario that could be based on our simulation results is that compressional MHD oscillations of the near-Earth tail and possibly the plasmasphere exist in the 5-10 minute period range, driven by the enhanced plasma convection. Without ionospheric feedback these oscillations would persist but not reach large amplitudes. In the presence of ionosphere-magnetosphere coupling, however, these oscillations are usually damped and unobservable, but during substorm they become unstable and reach large amplitudes. The fading and subsequent brightening are respectively the last trough and crest of the wavy motion in this scenario.

Thus the simulation results suggest that the auroral fading is a large-scale magnetospheric phenomenon related to plasma temperature and motion. This result is an important addition to the fading observations from which the cause or spatial extent of the fading could not have been resolved.

In addition to the purely magnetospheric causes, precipitation changes due to field-aligned potential drops are also included in the model, but the potential drop generally affects the ionospheric conductivity less than the magnetospheric source plasma density and temperature. However, the overall effect of the ionosphere is crucially important: If we repeat the simulation with the ionospheric feedback removed, only large-scale pulsations in the 10-minute period range (same period range as Pc-5) occur, but no clearly identifiable breakups or fadings take place. Overall the fading seems to be rather sensitive to various models employed in the simulation. For example, if the model for the Lyons–Evans–Lundin K parameter is modified, the fading may disappear. The same effect may also be obtained by altering the T_e/T_i ratio artificially at the earthward boundary of the simulation box.

Maybe the most evident shortcoming of the simulation is that the time scale of a substorm cycle appears to be too short, e.g. in our example the interval between two breakups is only 40 minutes. From this perspective the processes appearing in the simulation would be more appropriately called auroral activations than substorms. The reason for the unusual speed of evolution may simply be that the magnetospheric simulation box is only a subregion of the magnetotail. Another possible explanation is the fact that the tail convection is kept at a high value (corresponding to 0.3 mV m^{-1} electric field) all the time, i.e. for an hour, which may not be a very usual case in reality. As computing time allows, we will perform more simulation runs to test these possibilities in the future.

This paper was devoted only to auroral fading. Future work will deal with the presence of other substorm-related features in the simulation model, as well as further development of the model itself. However, this work has demonstrated the usefulness and power of a semiglobal coupling model, which lies in between traditional two-dimensional ionosphere-magnetosphere coupling models and truly global MHD simulations.

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Figure 1. Simulated height-integrated Pedersen conductivity as a color intensity plot at five consecutive moments before fading at 42 min (topmost large panel), during the fading (43, 44, and 45 min), and just after the breakup (46 min). Magnetic coordinate lines are shown on white. The IMAGE magnetometer cross is displayed as a red line.

Figure 2. Simulated ground magnetogram north component at the locations of the stations of the IMAGE chain. Breakup times as determined from conductivity distributions are shown as dotted vertical lines. The equivalent current is everywhere westward. B_x values corresponding to zero current (baseline levels) are slightly above the highest peaks for each station.

Figure 3. Simulated height-integrated Hall conductivity as function of time and magnetic latitude. The two onsets at t =7 min and t =45 min (dashed vertical lines) and preceding fadings at t = 6 min and t =44 min are clearly visible. After the first onset (approximately for 15 min $< t <$ 35 min) there is a double oval situation, and the magnetogram is remarkably calm.

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