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Generation, propagation and consequence of field-aligned currents during substorm expansion

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A substorm is one of the most drastic phenomena in the magnetosphere and the ionosphere. The aurora suddenly brightens, and an auroral electrojet current begins to flow in the polar region. During the substorm expansion, a large amount of energy exceeding 10^{11} W is consumed in the polar ionosphere due to Joule heating. The intensification of the auroral electrojet is directly driven by field-aligned currents (FACs) flowing into and away from the polar ionosphere. The brightening of the aurora is known to coincide with the upward FACs. In that sense, abrupt intensification of field-aligned currents (FACs) is a key in understanding the substorm.

The global magnetohydrodynamics (MHD) simulation, REPPU, is capable of reproducing the abrupt intensification of the FACs and auroral electrojet [1]. Assuming that the FACs are accompanied by Alfvén waves, we traced packets of the Alfvén waves backward in time from the onset position in the ionosphere in global MHD simulation. We found that the Alfvén waves are generated near the equatorial plane where azimuthally moving plasma works against the magnetic tension force, that is, $\mathbf{V}\cdot\mathbf{F}_t < 0$, where $\mathbf{V}$ is the plasma velocity, and $\mathbf{F}_t$ is the magnetic force density. The FACs were generated in the same region due to field-aligned gradient of space charge and curvature effect as well. The Alfvén waves did not propagate along the magnetic field line because of the presence of bulk flow of plasma, implying that the FACs do not necessarily flow along the magnetic field lines [2].

$\mathbf{J}\cdot\mathbf{E}$ has commonly been used to identify the region where the Alfvén waves and the FACs and generated. Here, $\mathbf{J}$ denotes the current density and $\mathbf{E}$ the electric field. In the ideal MHD approximation, $\mathbf{J}\cdot\mathbf{E} = \mathbf{V}\cdot\mathbf{F}_t + \mathbf{V}\cdot\mathbf{F}_b$, where $\mathbf{F}_b$ is the magnetic pressure force density. The first term on the right-hand side is likely associated with the generation of the Alfvén waves, whereas the second one is related to compression. The compression takes place frequently in the magnetosphere, so that the contribution from the second term to $\mathbf{J}\cdot\mathbf{E}$ can be significant, in particular, during the substorm. In the same MHD simulation, the region where $\mathbf{J}\cdot\mathbf{E} < 0$ appears off-equator just before the beginning of the substorm expansion onset, which is different from the region where $\mathbf{V}\cdot\mathbf{F}_t < 0$. Use of $\mathbf{J}\cdot\mathbf{E}$ as an indicator of the generation of the Alfvén waves may lead to the conclusion that the substorm-associated Alfvén waves (the FACs) are generated at off-equator. However, in the off-equator region, $\mathbf{V}\cdot\mathbf{F}_t > 0$, so that the Alfvén waves are unlikely to be generated.

The earthward fast flow originates from the near-Earth reconnection site, implying conversion from the magnetic energy to the kinetic and internal energy as previously suggested. When the earthward fast flow is decelerated, compression takes place, and the kinetic energy is converted to the magnetic energy and the internal energy. Due to the compression, the magnetic and plasma pressure increase near midnight, accelerating plasma in the dusk and dawn directions. That is, the magnetic energy and the internal energy are converted to the kinetic energy. As the plasma moves in the azimuthal direction, the Alfvén waves are excited, meaning that the kinetic energy is converted to the magnetic energy perpendicular to the magnetic field [2]. In this way, the energy becomes concentrated within a narrow region for powering the substorm expansion onset, which is consistent with observations.

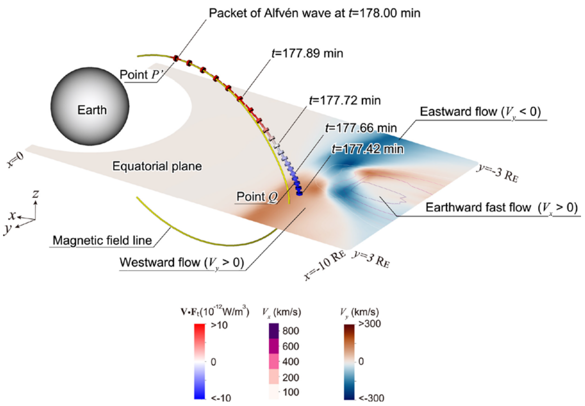

Figure 1. Global MHD simulation result. The small cylinders indicate the positions of the packet of the Alfvén waves, which are supposed to carry perturbations associated with the FACs causing the substorm expansion onset. Color on the magnetic field line indicates the value of $\mathbf{V}\cdot\mathbf{F}_t$. The thin tubes extending from the cylinders indicate the magnetic field lines. The horizontal plane represents the equatorial plane. Color shaded on the equatorial plane represents the y-component (dawn-dusk direction) of plasma velocity (V_y). Color of the contour lines indicates the x-component of plasma velocity (V_x). [2]

References

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