The Terrestrial Magnetosphere: A Half-Wave Rectifier of the Interplanetary Electric Field

Abstract. *A study of geomagnetic disturbances during 1967 and 1968, for which in situ solar wind observations are available, reveals that the magnetosphere acts as a half-wave rectifier of the interplanetary electric field. The rate of injection of energy into the magnetosphere, as inferred from the strength of the disturbance, is approximately linearly proportional to the component of the electric field from dawn to dusk but is effectively zero if the electric field has a component from dusk to dawn.*

The hot highly ionized upper atmosphere of the sun, the solar corona, is continually expanding outward, becoming supersonic beyond about 30 solar radii. This supersonic solar wind confines the terrestrial magnetic field to a cavity called the magnetosphere with a blunt forward end, having a radius of curvature of about 10 earth radii, and a long tail, about 50 earth radii in diameter, extending far past the orbit of the moon in the antisolar direction (*1*). The terrestrial magnetic field efficiently shields the earth from the solar wind so that less than 1 percent of the incident energy enters the magnetosphere (*2*). An important feature of the transfer of energy into the magnetosphere is that it is not continuous but increases and decreases almost at random without accompanying changes in the kinetic energy of the solar wind.

The main solar wind parameter controlling the transfer of the kinetic energy is now known to be the direction of the interplanetary magnetic field (*3*). When the interplanetary magnetic field is antiparallel to the terrestrial field, the solar wind and magnetospheric fields merge to some extent and open the magnetosphere for the transfer of energy. When the fields are parallel, the magnetosphere is closed and the terrestrial magnetic pressure "stands off" the solar wind flow, preventing the transfer of energy. Although theoretical treatments of the merging process in two-dimensional geometries are available for guidance (*4, 5*), the three-dimensional magnetospheric merging problem has not been solved. Thus, we must rely on experimental observations to determine how the rate of merging depends on the direction of the interplanetary magnetic field.

We present here the first direct experimental confirmation of the simple assumption that the rate of energy transfer is proportional to the strength of the north-south component of the interplanetary magnetic field when this field is southward, that is, antiparallel to the terrestrial magnetic field, and zero when it is northward (parallel). This so-called rectifier assumption has already been used in deriving a moderately successful predictor of the intensity of auroral zone ionospheric currents, which are enhanced when the solar wind coupling increases (*6*). The same assumption has also been used in a model that successfully reproduces many of the features of the semiannual variation of geomagnetic activity (*7*). However, in neither of these studies were all possible merging laws examined. Furthermore, two-dimensional theoretical studies of the merging process suggest that the merging rate should slowly and continuously change as the interplanetary and magnetospheric magnetic fields rotate from a parallel to an antiparallel configuration (*4, 8*).

A more accurate statement of this model also requires a consideration of the rate at which the "mergible" interplanetary magnetic field is brought to the magnetosphere by the solar wind. This rate is the product of the solar wind velocity (V) and the north-south component of the magnetic field (*Bns*). In the solar wind plasma, resistive, inertial, pressure gradient and Hall effect terms in the generalized Ohm's law are small by comparison with this product, and thus it is a quite accurate measure of the dawn-dusk component of the interplanetary electric field. (By dawn-dusk we mean that component perpendicular both to the north-south direction and to the sun-earth line.) If the magnetic field has a southward component, the electric field component is directed from dawn to dusk; for a northward magnetic field component the electric field component is directed from dusk to dawn. Thus, in terms of the interplanetary electric field, the rectifier model states that the rate of energy transfer to the magnetosphere is zero for a dusk-to-dawn electric field and is proportional to the strength of a dawn-to-dusk electric field.

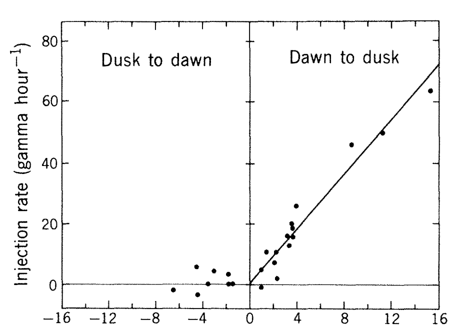

Fig. 1. The rate of injection into the magnetospheric ring current as measured by the rate of change of the *Dst* index for 23 intervals of steady solar wind flow, plotted versus the dawn-to-dusk component of the interplanetary electric field, E_y. The dawn-to-dusk component of the electric field is the product of the radial solar wind velocity and the north-south component of the interplanetary magnetic field. Positive or dawn-to-dusk electric fields correspond to southward magnetic fields, that is, antiparallel to the terrestrial magnetic field.

To test this model we have correlated interplanetary electric field data with a geomagnetic indicator of the rate of energy transfer to the magnetosphere. This indicator we derive from the so-called *Dst* index, which is in essence the longitudinal average of the disturbance in the horizontal component of the geomagnetic field observed at low latitudes. For constant solar wind conditions, the *Dst* index gives a direct measure of the energy in the magnetosphere in the form of energetic particles. These particles are injected into the magnetosphere and energized during energy transfer intervals and represent a major component of the total energy given to the magnetosphere by the solar wind.

However, the quantity that we desire is the rate at which energy is transferred. To a good approximation, this would be given directly by the rate of change of the *Dst* index except that the energetic particles are lost to the atmosphere with a time scale that is not greatly different from their injection time scale. To take into account the decay rate of the energetic particles, we use the exponential decay time of 8 hours found in a study by Shevnin (*9*), which we have verified independently.

We are now in a position to investigate the dependence of the rate of injection into the ring current on the interplanetary electric field. First, we select intervals of constant solar wind parameters and, at most, slowly changing interplanetary magnetic field. We then measure the rate of change of the *Dst* index, correcting for its intrinsic decay during the injection period. The results for 23 injection events are shown in Fig. 1, plotted versus the dawn-to-dusk component of the interplanetary electric field.

The line drawn on the right-hand panel of Fig. 1 is the linear least-squares fit to the points in the right-hand panel. Effectively, this line passes through the origin. The points in the left-hand panel have not been fitted but are clearly consistent with zero injection for dusk-to-dawn electric fields, that is, northward interplanetary magnetic fields. Thus, as measured by injection into the ring current, the magnetosphere acts as a half-wave rectifier not interacting for northward magnetic fields but interacting proportionally to the rate of transport of southward magnetic fields to the magnetopause (*10*).

We have not measured the merging rate in this study, for we cannot be certain that the particle injection rate is linearly proportional to the merging rate. However, it is difficult to conceive of a mechanism whereby the injection rate depends on a rectified interplanetary electric field while the merging rate does not. Thus, it appears that the merging rate is effectively zero for northward magnetic fields. Further support for this contention is provided by the fact that perturbation in the horizontal component of polar cap magnetograms, presumably caused by antisolar convection driven by the merging process, also drops to zero for northward magnetic fields (*11*). Thus, the available observational data support the popular assumption about the dependence of merging on the direction of the interplanetary magnetic field, that the terrestrial magnetosphere acts as a rectifier. We would expect the Jovian (*12*) and Mercurian (*13*) magnetospheres to behave in a similar manner.

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References and Notes

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14. We are indebted to J. Binsack, C. P. Sonett, and D. S. Colburn for making available to us their Explorer 33 and Explorer 35 measurements of the solar wind and interplanetary magnetic field. The ground-based records, from which the *Dst* values were produced, were obtained from the World Data Center A, Boulder, Colo. This work was supported in part by National Science Foundation grant GA 341484 and Office of Naval Research grant N0014-69-A-200-4016.

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Lepidopteran Leaf Mine from the Early Eocene Wind River Formation of Northwestern Wyoming

Abstract. *A lepidopteran mine, probably of* Phyllocnistis, *on a leaflet impression of* Cedrela *(Meliaceae) discovered in late early Eocene strata near Dubois, Wyoming, is the earliest record of leaf mining and of the Phyllocnistidae. Considerable prior evolution of the mining habit, antiquity of the* Cedrela-Phyllocnistis *relationship, and subtropical climatic conditions are indicated.*

A single lamina bearing the track of a serpentine mine was found during the course of paleobotanical collecting in 1969 in the Sheridan Pass area southwest of Dubois, Wyoming (Fig. 1) (*1*). Subsequent examination led to the identification of the lamina as a leaflet of the genus *Cedrela* and of the mine as a probable member of the modern genus *Phyllocnistis*.

The leaflet bearing the mine occurs in a 0.6-m-thick bed of light gray, tuffaceous, microcross-to-parallel laminated claystone and siltstone apparently deposited in a swamp (*2*). This bed contains a rich and diverse megafossil plant assemblage laterally equivalent to the Coyote Creek flora of the Fish Lake Quadrangle to the east (*2*). The bed containing this flora is part of what Rohrer (*2*) calls the "lower volcaniclastic unit" (Fig. 1) and is tentatively correlated with the upper part of the Wind River Formation in the DuNoir and East Fork areas lying to the east. In the vicinity of Sheridan Pass the lower volcaniclastic unit consists of approximately 365 m of volcanic granulite, sandstone, siltstone, and claystone, with minor amounts of conglomerate. A "variegated unit," which is also tentatively correlated with the Wind River Formation, conformably underlies the unit, while an unconformity separates the lower volcaniclastic unit from an overlying "upper volcaniclastic unit." This latter sequence is tentatively correlated with the Tepee Trail Formation of the DuNoir area (*2*).

The Coyote Creek flora appears to lie stratigraphically above the level of the Wind River flora in the DuNoir area, where associated beds contain vertebrate fossils of Lost Cabin age (*2, 3*). A lapilli tuff found 46 to 49 m above the Coyote Creek floral unit gives an uncertain potassium-argon age of 50 million years (*2*). Fossil floras and a potassium-argon age from a bentonite bed in the upper volcaniclastic unit in the Kisinger Lakes Quadrangle to the north give ages of middle Eocene and 49.3 million years, respectively (*2, 4*). Thus, the Coyote Creek flora appears to date from the Lost Cabin provincial substage of the late early Eocene, between 50 and 51 million years ago (*5*).

A number of examples of leaflets and whole leaves identical in internal architecture to the mined lamina occur in the leaf bed at the locality and in correlative units (Fig. 2). These indicate that the lamina is part of a compound leaf with five to seven leaflets. Leaflet shape ranges from symmetrical (for terminals) to slightly asymmetrical (for laterals) and elliptic to

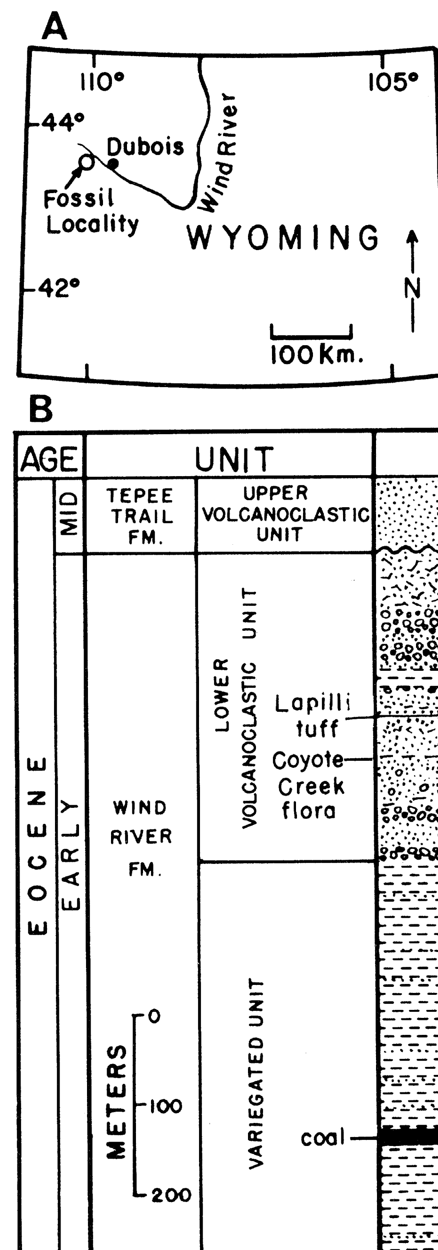

Fig. 1. Geographic location (A) and stratigraphic setting (B) of the leaf mine locality. The mine was found at the level of the Coyote Creek flora. Stratigraphic section and correlations after Rohrer (*2*).