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Energy transfer via region 2 currents: A test of the standard magnetosphere-ionosphere coupling theory

George Siscoe
Center for Space Physics, Boston University, Boston, Massachusetts

Gang Lu
High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado

Abstract. The magnetosphere-ionosphere coupling theory associated with the names of Fejer, Vasyliunas, Swift, Wolf, and others can be used to predict that in steady state the region 2 currents transfer no net energy between the ionosphere and the magnetosphere, but when the transpolar potential drop increases, region 2 currents transfer energy away from the ionosphere into the magnetosphere. Both properties are counterintuitive and differ from the "normal" properties exhibited by region 1 currents, which in steady state or otherwise consistently deliver energy to the ionosphere to feed Joule dissipation. We extend the theory to include the effects of charge exchange so that it can be applied to magnetic storms. We conclude that charge exchange also extracts energy from the ionosphere via region 2 currents. To test these predictions of unexpected properties, we use the technique of assimilative mapping of ionospheric electrodynaics (AMIE). From AMIE-derived values of ionospheric electrical potentials and field-aligned currents for a well documented magnetic storm, we compute the direction and flux of energy flowing between the ionosphere and the magnetosphere. Region 2 currents indeed transfer energy out of the ionosphere during the storm main phase, when the transpolar potential drop increases to its storm time value. The rate of energy transfer is greatly suppressed late in the recovery phase when conditions approximate steady state. Also the data are consistent with charge exchange acting to extract energy from the ionosphere via region 2 currents. Thus the test confirms two of the predictions and is consistent with the third. For this storm the region 2 upward energy flux is at most about 30% of the energy that goes into the ring current to account for the growth of Dst.

1. Purpose of the Work

Our goal is to describe and test the basic properties of the transfer of energy by region 2 currents as these properties follow from the magnetosphere-ionosphere coupling theory associated with the names of Fejer, Vasyliunas, Swift, Wolf, and others. (To avoid repeating this circumlocution, we refer to this theory as the standard MIC theory.) These properties are sufficiently different than the properties of energy transfer by region 1 currents (which are rather intuitive) and sufficiently unknown that it seems not unwarranted to give a special treatment of them here. A special treatment is further warranted because the means to check these energy transfer principles have now become available through the assimilative mapping of ionospheric electrodynamics (AMIE) technique. Two of the properties of energy transfer pertaining to region 2 currents have been described previously [*Siscoe*, 1982]. We add a third property here. None has been tested, as far as we know.

The standard MIC theory had reached a more or less complete formulation by the mid 1970s, and it has held up since then without damaging threats to its basic correctness. The present exercise also leaves it uninjured. Nonetheless, it does serve to explore some little appreciated properties of the theory that have contemporary relevance. For instance, in interpreting Poynting flux measurements from polar-orbiting satellites, the operation of energy transfer by region 2 currents can be mistaken for the operation of an atmospheric dynamo. Also since region 2 currents connect the ionosphere to the ring current, the energy they transfer is relevant to ring current energy budgets, a topic of present emphasis in the Geospace Environment Modeling (GEM) Inner Magnetosphere Campaign. Before we start the tests, however, we should review what it is we are testing.

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2. What is the Standard Magnetosphere-Ionosphere Coupling Theory?

The standard MIC theory says that the ionosphere and the magnetosphere are tightly coupled by the requirement that Birkeland currents generated in one domain precisely match those generated in the other where they meet at the top of the ionosphere; otherwise, space charge would build up at the interface. In the ionosphere the laws that govern the creation of Birkeland currents are the ionospheric Ohm's law and current continuity. In the magnetosphere they are particle drift physics and current continuity. By equating the Birkeland currents generated in each domain under a consistently mapped electric field, one obtains the governing equation of the standard MIC theory. (For a comprehensive review, see *Wolf* [1983]. The governing equation in Wolf's review is (57)) The theory was given its conceptually defining form by *Fejer* [1963, 1964], and it evolved into a computationally mature form as developed by Wolf a decade later [e.g., Wolf, 1974].

To explain our approach to treating the energy flow properties of the standard MIC theory, we must fill in a few historical details. Otherwise there is room for confusion, for there are two formulations of the theory. We have chosen the one best suited for a heuristic explanation of energy flow properties, rather than the one best suited for carrying out numerical computations. The two formulations were both introduced by Vasyliunas. In one, the magnetospheric plasma enters the expression for the coupling Birkeland currents in the form of a gradient of plasma pressure [*Vasyliunas*, 1970] (this is the formalism discussed by *Wolf* [1983]); in the other, magnetospheric plasma enters in the form of flux tube content, that is, as a particle number density normalized to the volume of a flux tube of unit cross-sectional area in the ionosphere [*Vasyliunas,* 1972] (this is the formalism we use here). Let us call the first the pressure formalism and the second the conductance formalism, since the number density that distinguishes it is expressed as a pseudo-Hall conductance in the formalism. *Pontius* [1992] pointed out that the two formulations appear to be incommensurable, since in one magnetospheric plasma enters as pressure and in the other it enters as conductance. He noted further that to reconcile the two formulations as methods for discussing plasma distributions from initial and boundary conditions, it is essential that time dependence be included in the conductance formalism or, in steady state, that the plasma distribution in the conductance formalism be determined self-consistently beforehand. These are valid points. Since we have adopted the conductance formalism for its heuristic value, we must ensure that these stipulations are satisfied. In what follows, we indicate how they are satisfied.

3. A Test of the Energy Flow Properties of Standard MIC Theory as Applied to Region 2 Currents

As *Kennel* [1995, p. 62] notes, "The regions of field-aligned currents are regions of energy exchange between the magnetosphere and the ionosphere." When we ask the standard MIC theory to describe the behavior of the energy that flows between the ionosphere and the magnetosphere in the region 2 current system, it gives some unexpected answers. The theory actually sticks its neck out by predicting properties that are different than the properties of the region 1 system, which behaves "normally." Our aim here is to use the predicted unexpected properties of energy flow in the region 2 current system to test the standard MIC theory. We begin by stating what the unexpected properties are; then we show that the theory indeed predicts them. Following this, we show to what extent the predicted properties show up in an AMIE analysis of a well-observed magnetic storm.

First, however, we should state what is normal, or expected, behavior. How should one expect energy to flow between the ionosphere and the magnetosphere in the region 2 current system? *Sugiura* [1984] answered the question when he presented results from an analysis of DE 2 data showing that the Poynting flux associated with field-aligned currents carries energy into the ionosphere (he did not distinguish between regions 1 and 2 currents). He concluded (p. 880) that "the Poynting vector calculated from the observed **E** and **b** represents the ionospheric energy dissipation by Joule heating... This state is interpreted as being the usually prevailing mode of the magnetosphere-ionosphere coupling involving field-aligned currents." In this very reasonable view, the ionosphere represents a resistive load in a circuit that has a generator somewhere in the solar wind, for region 1 currents, and somewhere in the magnetosphere, for region 2 currents. By contrast, a mode which transfers negligible energy or which transfers energy out of the ionosphere would be considered unusual.

Lest there be some confusion over how one can speak about transferring energy between the ionosphere and the magnetosphere via region 1 currents or region 2 currents, let us review ultra briefly the treatment of Poynting's energy flux theorem that lets one speak so. Note first that, as depicted in the classical pattern presented by *Iijima and Potemra* [1976], both currents consist of a bipolar pair, that is, each has a part carrying current into the ionosphere and a part carrying current out of the ionosphere. One computes the power flowing into or out of the ionosphere carried by a bipolar current pair by integrating over the surface of the ionosphere the electrical potential multiplied by the vertical component of the current density [*Hill*, 1983, equation 11]. If the vertical component of current is measured positive upward, a positive power corresponds to energy flowing out of the ionosphere. If the induction field can be ignored compared to the potential field, which for this purpose is virtually always true at the ionospheric level, this area integral of vertical current density times electrical potential is formally identical to the Poynting flux out of the ionosphere. Thus, one can think of energy flowing along the region 1 and region 2 currents the way one thinks of energy flowing along the electric wire that connects an electrical outlet to an electric lamp. In this analogy, Sugiura's expectation can be restated by saying that the ionosphere is the lamp and the other end of the region 1 or region 2 wire connects to some power source.

Relative to this expectation, the standard MIC theory makes the following two unexpected predictions: (1) during quasi-steady-state convection, the region 2 currents carry virtually no energy between the ionosphere and the magnetosphere; and (2) when the transpolar potential drop increases, region 2 currents can carry appreciable energy away from the ionosphere into the magnetosphere [*Siscoe*, 1982]. Here the qualifiers "virtually no" and "appreciable" mean by comparison with an upper limit set by the total region 2 currents in amperes multiplied by the transpolar potential drop in volts. That is, standard MIC theory predicts that in their usual mode, the region 2 currents transfer energy at a negligible rate compared to the upper limit, and occasionally they operate in a mode in which they reverse the usual direction of energy flow. According to the theory, energy can flow out of the ionosphere at a rate approaching the upper limit when the transpolar potential drop increases by an amount comparable to the initial potential on a timescale short compared to the shielding timescale given by the theory. The prediction that region 2 currents carry energy outward following an increase in the transpolar potential drop is unique to this theory and, hence, provides an opportunity to construct a diagnostic test specific to the theory.

The test has two parts: (1) compute the power into or out of the ionosphere carried by region 2 currents during a time when there is no dramatic change in the transpolar potential drop to see if it is negligible compared to the upper limit (this is the harder part, for steady state means weak signals); and (2) compute the power at a time when the transpolar potential drop increases substantially and suddenly to see if there is an appreciable upward flux of energy. To carry out the tests, one needs synoptic maps of electric potentials and field-aligned currents. For this we use the data inversion technique called assimilative mapping of ionospheric electrodynamics (AMIE) formulated by *Richmond and Kamide* [1988]. The value of this technique has been well demonstrated for use as a tool in projects like this that need quantitative values of ionospheric electrodynamic parameters continuously distributed over synoptic scales. (For a recent example which discusses many details and which illustrates the power of the technique through numerous results, see *Lu et al.* [1996].)

The conditions of rapid, large increase in the transpolar potential drop and relatively steady transpolar potential drop are satisfied, respectively, during the main phase and the late recovery phase of a magnetic storm. Accordingly, we perform the test with data from a magnetic storm which satisfies two requirements: (1) the data coverage is adequate to ensure that the AMIE technique gives high quality results, and (2) the storm is nonpathological in the following respects: it is isolated, has a normal main phase and a normal recovery phase, and exhibits clearly identifiable and separable contours in the ionosphere corresponding to region 2 currents. The magnetic storm of April 16-17, 1994, satisfies these requirements.

Before presenting the results of the AMIE analysis of this storm, however, we review the theory behind the predictions that the analysis is meant to test: (1) region 2 currents carry negligible energy into or out of the ionosphere during quasi-steady-state conditions; and (2) they carry energy out of the ionosphere when the transpolar potential drop rises quickly compared to the shielding time. We add as a third prediction that charge exchange also extracts energy from the ionosphere via region 2 currents.

4. The Theory's Unique Predictions Regarding the Rate and Direction of Energy Flow

We mentioned that the standard MIC theory works by equating the Birkeland currents generated by the ionospheric Ohm's law to the Birkeland currents generated by magnetospheric particle drift physics. *Vasyliunas* [1972] showed that particle drift physics can be cast in the mathematical form of the ionospheric Ohm's law with a time-dependent source term (which he sets equal to zero, but which we must retain). Thus, the ionospheric and magnetospheric expressions for the Birkeland currents have formally the same Ohm's law structure. Equating the Birkeland currents from the two domains therefore gives an Ohm's law equation with a modified conductance and a time-dependent source term. This is a great mathematical simplification, which we use for its heuristic value.

For readers who like some physical insight to go along with theoretical formalism, we digress from proceeding directly to the predictions of this theory to develop the physical context behind it. It relies on two key assumptions: (1) in the part of the magnetosphere that produces region 2 currents (the inner edge of the plasma sheet), the electrons are cold compared to the ions, such that the electron thermal drifts can be ignored compared to their electric field drift; and (2) electrons readily flow up and down field lines to maintain charge neutrality with the ions. The first assumption is well justified by observations, which is why Vasyliunas made it. His analysis of OGO 1 and OGO 3 electron data revealed an "unexpected" sharp inner boundary to the electron plasma sheet. He called it a "hole." In the OGO data, the electron temperature plummets earthward of 10 Re, typically [*Vasyliunas*, 1968]. *Frank* [1967] had reached a similar conclusion (that electron temperatures are about an order of magnitude less than proton temperatures in the ring current during magnetic storms) also on the basis of OGO data. *Frank* [1971] extended the findings into a general synthesis in which a cool electron trough lies within the proton ring current. *Kennel* [1969] explained the cooling of the earthward electron plasma sheet population within the hot ion plasma sheet population, whose earthward extension forms the ring current, in terms of the great mobility of the electrons, which allows them to scatter and escape through the loss cone into the ionosphere and be replaced by cool ionospheric electrons before they convect into ring current distances. This differential cooling of electrons in the ring current region relative to ions take place starting with a plasma sheet population in which the electron temperature is already a factor of 7 less than the ion temperature [*Baumjohann*, 1993]. Thus, the first assumption is well justified. (One should not confuse the cool plasma sheet electron population that is the counterpart of the plasma sheet ion population whose earthward extension forms the ring current with the outer electron radiation belt, which has a different origin and dynamics.) The second assumption, that electrons readily flow up and down field lines to maintain charge neutrality with the ions, is generally accepted and noncontroversial. (There is a third assumption that field lines are equipotentials. This is probably a good assumption for region 2 currents. It could be relaxed with no significant change in the conclusions regarding field-aligned currents. It is retained for simplicity.) From these assumptions and the physics of particle drifts, the origin of Birkeland currents from the magnetosphere can be readily understood, as we now review.

Physically, field-aligned currents arise as electrons ExB drift across spatial gradients in the ion density. Electrons flow up and down field lines to keep the electron density equal to the ion density as the electrons traverse streamlines across which the ion density changes. Field-aligned currents can also arise if the ion drift is time dependent such that the density at some place increases or decreases. The electrons flow up and down field lines to neutralize the change in charge. *Vasyliunas* [1972] showed that in terms of generating field-aligned currents, these two processes (electrons drifting across spatial ion density gradients and time dependence in the ion density) are formally equivalent to a Hall current with a time-dependent source term. In the equations below, we have added a term to account for charge exchange of the energetic ions—for if the time dependence is due to charge exchange, there is no lost charge and, hence, no compensating electron motion along field lines.

In a purely Hall-conducting medium, field-aligned currents can only arise from gradients in the Hall conductance. In the conductance formalism, therefore, field-aligned currents arise from gradients in the magnetospheric Hall conductance (that is, from gradients in the total ion flux tube content) together with a time-dependent source term (see the appendix for a derivation):

$$J_z = \hat{z} \cdot \nabla\phi \times \nabla\Sigma_H^* - e\partial N/\partial t - eL_{ex} \tag{1}$$

where J_z is the upward component of the field-aligned current density generated in the magnetosphere, $\hat{z}$ is the upward pointing unit vector, ϕ is electrical potential, $\Sigma_H^* = eN/B_i$ is the effective magnetospheric Hall conductance, N is the flux tube content (from the ionosphere to the equator), B_i is field strength, and L_{ex} is the charge exchange loss rate from the flux tube. All quantities are evaluated at the surface of the ionosphere. The time derivative acts as a pure source term for field-aligned currents. The charge exchange term is added to treat the case of magnetic storms, where charge exchange is a significant loss process for energetic ions.

Equation (1) represents the conductance formulation of the standard MIC theory, which, because of its relative simplicity (containing flux tube content instead of pressure), we will use heuristically to demonstrate the energy transfer properties stated earlier. Let us first indicate how our use of it satisfies Pontius' stipulation that the Σ_H^* function be obtained by a process that guarantees that all terms on the right-hand side of the equation have been determined simultaneously and self-consistently. They may not be specified independently and arbitrarily. This stipulation is satisfied because we assume that Σ_H^* has been determined by nature (which presumably calculates everything on the right-hand side of the equation self-consistently). We merely use the equation to derive certain properties that must be true of such a function. We do not specify the function; instead we say what properties it has because it must satisfy the equation.

The project is to test whether measured region 2 currents have the same energy-transferring properties as the currents given by J_z in (1), which henceforth, we refer to as Vasyliunas currents. First, we must use (1) to verify the claim made earlier that Vasyliunas currents transfer negligible energy in steady state and they deliver energy upward when the transpolar potential drop increases.

The flow of power out of the ionosphere carried by Vasyliunas currents is found, as noted earlier, by integrating over the ionospheric surface (with surface element $d\sigma$) the product of (1) and the electric potential.

$$PowerOut = \int_{ionosphere} \phi \nabla\phi \times \nabla\Sigma_H^* \cdot \hat{z}\, d\sigma - \int_{ionosphere} e\phi(\partial N/\partial t + L_{ex})\, d\sigma \qquad (2)$$

We are interested in the area in the ionosphere that contains the region 2 currents. We take this area to be an annular surface that extends from a low-latitude boundary where Σ_H^* is zero to a higher-latitude boundary where (for reasons made clear below) the corresponding equatorial field strength is constant. In the equatorial magnetosphere this corresponds to a line of constant B that circles the Earth (i.e., it does not touch the magnetopause) inside of which most of the region 2 currents are created. It must be possible to find such a line for otherwise, in the ionosphere, region 2 currents would touch the polar cap boundary, which corresponds to the magnetopause. But this would be inconsistent with the known geography of region 2 currents, that they are separated from the polar cap boundary by region 1 currents [*Iijima and Potemra*, 1976].

Now, apply Stokes' theorem to the first integral in (2) to find

$$PowerOut = \oint_{h.l.boundary} \Sigma_H^* \phi\, d\phi - \int_{ionosphere} e\phi(\partial N/\partial t + L_{ex})\, d\sigma \qquad (3)$$

where the line integral is over the higher-latitude boundary of the annulus. The line integral over the lower-latitude boundary of the annulus disappears since, by choice, $\Sigma_H^* = 0$ there.

Consider first a situation in which nature has brought about a steady state situation. Let us idealize further by removing the exosphere so that the steady state situation has become established in the absence of charge exchange. Then the integral over the high-latitude boundary vanishes, as we now show by first establishing that, on the boundary, Σ_H^* is a function of ϕ. If this is so, then the integrand becomes a perfect differential, and a closed line integral over a perfect differential is numerically zero. To establish that in this case Σ_H^* is a function of ϕ, consider ions in the equatorial plane (for simplicity) moving under magnetospheric convection from the tail, crossing our bounding constant-B line into the inner magnetosphere, there creating region 2 (Vasyliunas) currents, then crossing the constant-B line again as they move outward, heading sunward toward the dayside magnetopause. Because our chosen boundary to the magnetosphere's region 2 domain is a line of constant B, every ion streamline must leave the region 2 domain at the same potential ϕ at which it entered. This follows from the conservation of energy and the constancy of the first adiabatic invariant. We need only add that the number of ions in a unit magnetic flux tube (which is proportional to Σ_H^*) is constant along an ion streamline (for a nice proof of this theorem, see *Wolf* [1983, p. 316]). Thus, the values of Σ_H^* and ϕ are the same at the entry-crossing point and exit-crossing point of each ion streamline. Formally, this means that Σ_H^* can be considered a function of ϕ on the boundary, which is a sufficient condition that the closed line integral in (3) vanish. Less formally, we reach the same conclusion by noting that since the constant-B boundary is a streamline for the ions' thermal drift, they are carried across the boundary by their ExB drift alone. From this it follows that the differential $d\phi$ (which determines the local value of E tangent to the boundary) must have opposite signs at the entering and exiting points of an ion streamline, while, as we have just shown, the magnitude of the integrand at the entering and exiting points is the same. Hence, the contribution to the integral at the exit point cancels the contribution at the entry point (they have the same magnitudes but opposite signs), and again the closed line integral vanishes.

Since the boundary was chosen to contain all significant region 2 currents, the result says that in steady state (i.e., when the second integral in (3) vanishes), the net flow of energy that Vasyliunas currents carry between the ionosphere and the magnetosphere is effectively zero. This does not mean, however, that over the whole region 2 area, the upward and downward directed Poynting fluxes are zero. Instead it just means that over this area the upward and downward fluxes cancel each other to a good approximation.

After having shown that in steady state and in the absence of charge exchange, the line integral in (3) vanishes for a naturally arising distribution of Σ_H^* across ion streamlines, we note as a special example the case usually treated in analytic studies: $\Sigma_H^* = const$ within an annulus in the ionosphere and zero elsewhere [e.g., *Vasyliunas*, 1972]. (*Pontius* [1992] noted that in the absence of charge exchange, this distribution can exist in steady state; so equation (1) holds.) Then Σ_H^* can be factored out of the integral, and the integral vanishes trivially. As a check on the procedure, one can solve this case fully analytically. In this case the Vasyliunas currents flow as sheet currents at the low-latitude border of the annulus. Their amplitude turns out to be proportional to the azimuthal derivative of the potential at the border. Thus, the closed azimuthal integral around the low-latitude border of the annulus of the product of the current and the potential (which gives the power out) again becomes a closed line integral over a perfect differential ($\phi d\phi$), which vanishes.

(It might seem strange that we have deduced so much about the energy-transferring properties of region 2 currents without mentioning the region 1 currents, which are the main supplier of power from the magnetosphere to the ionosphere. Actually, the region 1 currents are playing a major, behind-the-scenes role in giving the region 2 currents their peculiar properties. The interplay between region 1 and region 2 currents which results in region 2 currents having the properties as stated is the subject of *Siscoe* [1982]. The discussion given there is too long to repeat here, and it is peripheral to the purpose of this paper. Nonetheless, in the interest of completeness, the main conclusion can be summarized briefly. We have concluded here that in steady state in the absence of charge exchange, the region 2 currents carry virtually no energy between the ionosphere and the magnetosphere. How can this be? Must not the closure of region 2 currents in the ionosphere necessarily cause Joule dissipation? Well no, not necessarily. Here is where region 1 currents come in. To see what happens, think first about the case with no region 1 currents. Then it is certainly true that region 2 currents would dump energy into the ionosphere in the form of Joule dissipation. But we need to state this obvious fact using the surface integral of $J.\phi$ formalism, in which power into the ionosphere corresponds to region 2 currents coming down where the potential is higher, on average, than where region 2 currents go up. What the region 1 currents do is to rotate the potential pattern such that region 2 currents come down where the potential is about equal, on average, to where region 2 currents go up. Then the surface integral over $J.\phi$ virtually vanishes, since the currents change sign from dawn to dusk, but at the latitude of the region 2 currents, the potential is about the same at dawn and dusk. This is because at the latitude of the region 2 currents, the pattern has rotated such that the potential changes sign from noon to midnight. (We are using the dawn-dusk and noon-midnight directions loosely; the real directions are rotated somewhat relative to these, but the operational point is that at the latitude of the region 2 currents, the potential pattern is rotated 90º relative to the region 2 current pattern.) Region 1 currents are essential to set up the rotation of the potential pattern that results in virtually zero net energy transfer by region 2 currents. Now, the fully self-consistent MIC equations know all this and have taken the role of the region 1 currents into account already to create the naturally arising, steady state situation with which we start the discussions in this paper.)

Consider next a situation in which the system has reached steady state in the presence of charge exchange. We can use the insights just gained by considering the steady state case to give a simple heuristic interpretation to the combined line integral and charge exchange integral in (3). In steady state they give the net power out of the region 2 domain carried by energetic ions or by fast neutrals created by charge exchange of energetic ions (charge exchange leaves low-energy ions behind, and thus, results in a net loss of energy from the region 2 domain). Since this is a steady state situation, the net power lost this way to the region 2 domain must be replaced from the ionosphere as power carried up by region 2 currents. That is the simple interpretation. To see that it makes sense, let us look more closely at the role of the line integral. It gives the net energy flux that the drifting ions carry outward across the boundary of the region 2 domain, that is, the total outward energy flux minus the total inward energy flux (this follows since $\Sigma_H^* \phi d\phi = (e\phi)N(E/B)dl$ where E is the tangential component of the electric field and the sign of the entire term is positive for outward directed E/B). In steady state with no losses these fluxes are necessarily the same (as much energy flows into the region 2 domain as flows out) and no net power deficit exists to be supplied by region 2 currents. This is the result we derived formally above. With charge exchange losses occurring within the region 2 domain, however, more energy leaves the domain per unit time than the ion flux carries across the boundary into the domain. This is so because charge exchange removes energy from the domain by making neutrals out of ions whose energy has necessarily gone up since they entered the domain, for the entire domain is closer to the Earth (and, therefore, at higher field strengths) than the boundary. If instead of suffering charge exchange, these ions had drifted through the region 2 domain and reached the outgoing boundary on the other side, they would have returned to the boundary with the energy with which they entered. But since they are lost in the interior of the domain, where they have gained energy since crossing the boundary, they take an excess of energy with them when they leave as neutrals. So there is a net loss of ion energy per unit time from the region 2 domain, which in steady state is supplied by power carried up from the ionosphere by region 2 currents. Note that the charge exchange situation involves both integrals, for, since energetic ions are lost, the naturally arising Σ_H^* cannot be constant on flow streamlines, which is a requirement for the first integral to vanish. The combination of the two integrals gives the net sum of the differences between the energy that charge exchange ions have when they enter the region 2 domain and the energy they have when they charge exchange within the domain. It is this difference that must be supplied by region 2 currents.

Now let us add the time-dependent term and drop charge exchange, to treat time dependence by itself. As a factor in the power budget, the integral with $\partial N/\partial t$ has a similar interpretation as the charge exchange integral. Consider a time-dependent situation in which the plasma sheet encroaches earthward, which is the magnetosphere's response to an increase in the transpolar potential drop. The area integral in this case is a nonzero, negative definite number because of a necessary correlation between the change in the transpolar potential drop and $\partial N/\partial t$. The correlation is this: An ion moves earthward by falling through a potential drop to acquire a greater gyroenergy to keep its μ constant as it moves into higher magnetic fields. Thus, ions reach their earthwardmost limit at the point along their drift path where the potential is most negative. Restated in a way that relates directly to the area integral in (3), $\partial N/\partial t$ is positive where ϕ is negative, which gives the integral a nonzero, negative definite value. Therefore, its contribution to the PowerOut that (3) computes is a nonzero, positive definite value. In this time-dependent situation, as in the charge exchange situation discussed above, the line integral does not vanish since the very fact of plasma sheet incursion means that during this time more particles enter the region 2 domain than leave it. Thus, by the same reasoning used in the charge exchange case, it is the combination of the time-dependent integral and the line integral that gives the power that must be supplied to carry the incursion through its time-dependent phase. (Note that this discussion is not inconsistent with the Pontius stipulation. We are not postulating what Σ_H^* or $\partial N/\partial t$ is. We are merely using (3) to show that as they arise naturally, they are coupled in a necessary way.)

In summary, we have drawn three conclusions from the conductance formulation of the standard GIC theory of region 2 currents: (1) in steady state, if we ignore charge exchange, Vasyliunas currents in the region 2 domain transfer essentially zero net power between the ionosphere and the magnetosphere; (2) when the transpolar potential drop increases (or more generally, when the plasma sheet moves earthward), Vasyliunas currents in the region 2 domain transfer net power out of the ionosphere into the magnetosphere; and (3) in steady state but with significant charge exchange loss, Vasyliunas currents in the region 2 domain also transfer net power out of the ionosphere into the magnetosphere.

The next section reports on a project to see if observed region 2 currents behave like Vasyliunas currents in the region 2 domain. For this we apply the power of the AMIE technique to data pertaining to the magnetic storm of April 17, 1994, which received relatively good data coverage and which exhibited a relatively uncomplicated life cycle as indicated by Dst.

5. AMIE Results for the Storm of April 17, 1994

During the storm period of April 17, 1994, there were 123 ground magnetometer stations monitoring the magnetic perturbations globally. The data coverage in the northern hemisphere was particularly good, better even, through the addition of more Russian stations, than the coverage available for the study presented by Lu et al. [1996]. The magnetometer data were averaged over 5-min, with a quiet-day baseline removed for each individual station. Ionospheric conductances used in this study were obtained by the modified statistical model of *Fuller-Rowell and Evans* [1987] with the magnetic perturbations measured by the magnetometers, using an empirical formula [*Ahn et al.*, 1983]. Since polar-orbiting satellites, such as DMSP and NOAA spacecraft, take approximately 20 to 25 min to pass the polar cap and 100 min to orbit the Earth, we did not use the satellite ion drift and precipitating particle data in this study in order to avoid possible intermittent convection and/or conductance alterations in the vicinity of the satellite track. The ionospheric electric potential and other electrodynamic fields are derived using the AMIE technique. (See *Lu et al.* [1996] for more details and references.) The representative AMIE patterns of ionospheric electric potential, field-aligned current, and the electromagnetic energy flux are shown in Figure 1 for two particular UT times. The electromagnetic energy flux is the product of electric potential and field-aligned current.

At 0400 UT, during the main phase of the storm, the electric potential pattern consists of two cells, with the morning cell intruded into the nightside. The distribution of field-aligned currents, in spite of the small-scale structures, show the upward region 1 and downward region 2 currents on the dawnside, and the downward region 1 and upward region 2 currents on the duskside. In the midnight sector, however, the duskside downward region 2 currents connect with the downward region 1 currents from the dawnside, forming a triple current sheet. Such a triple current sheet is a result of the intensification of the westward electrojet associated with substorms [*Lu et al.*, 1996]. Because of the complexity in the midnight sector, in this study we exclude the region between 2100 MLT and 0300 MLT. We defined the boundary between the region 1 and region 2 currents as the lowest-latitude boundary (above 50°) where field-aligned currents change polarity from upward to downward on the dawnside, and from downward to upward on the duskside. The total region 1 currents are then one-half the integral of the absolute values of the downward currents between 0300 and 1200 MLT and the upward currents between 1200 and 2100 MLT above the region 1/2 boundary. Similarly, the total region 2 currents are one-half the integrated dawnside upward currents and duskside downward currents below the boundary.

The same boundary between the region 1 and region 2 currents as defined above is used to separate the electromagnetic power associated with the region 1 and 2 current system. The net region 1 electromagnetic power is the energy fluxes integrated over the region 1 current region, and mutatis mutandis, the same for region 2 currents. One can see clearly the outward energy flux over the region of dawnside region 2 currents, shown as dashed contours. At 2030 UT, the recovery phase of the storm, the electric potential, field-aligned current, and electromagnetic energy flux are all weakened. There is outward flow over the entire polar region.

We return to Figure 1 after reviewing the storm. Figure 2, with eight data fields, describes the event (top panel) and quantifies the energy flow rates (bottom panel). Before we go into the description and the interpretation, however, a remark about expectations is appropriate. In general, the data fields in the figure exhibit a single large-amplitude cycle on which high-frequency, and in some cases large-amplitude, oscillations occur. The oscillations might reflect the influence of substorms, or the inherent range of variability in the technique, or both. Our interest is in the broad features, the single cycles, and their relative shapes and phases. The following discussion, therefore, refers to the curves as if viewed through a low-pass filter, which suppresses the oscillations.

Consider first the top panel in the figure. The storm itself, defined in Dst by a 200 nT main phase and a following recovery phase, lasted about a day. The main phase lasted about 10 hours. The traces of the polar cap potential drop and of the region 1 and 2 currents mimic the Dst trace in general outline. The peak potential drop is about 230 kV, the peak total region 1 current about 8 MA, and the peak region 2 current about 5 MA. These give peak upper limits on the power transferred by the region 1 and 2 currents of about 1800 GW and 1200 GW, as shown in the lower panel, which we turn to now.

Look first at the two power curves for the region 1 currents. When smoothed, the upper-limit curve peaks out at about 1300 GW. The net power (based on integrating the potential times the field-aligned current density over the area occupied ~~by~~ region 1 current contours) tracks the upper limit fairly closely, and as required, at all times remains less than the upper limit. Also at all times, the net region 1 power is negative, which means region 1 currents are transferring energy into the ionosphere. This is the expected result, which *Sugiura* [1984, p. 880] described as "being the usually prevailing mode of the magnetosphere-ionosphere coupling involving field-aligned currents." His statement of how most researchers think field-aligned currents ought to work makes the net power curve for region 2 currents especially interesting. During most of the main phase, region 2 currents are transferring energy out of the ionosphere. (Because the net power computed for region 2 currents turns out to be typically a factor of 5 smaller than the net power computed for region 1 currents, the values of net power computed for region 2 currents have been multiplied by 5 to give them comparable visibility.) The result demonstrates

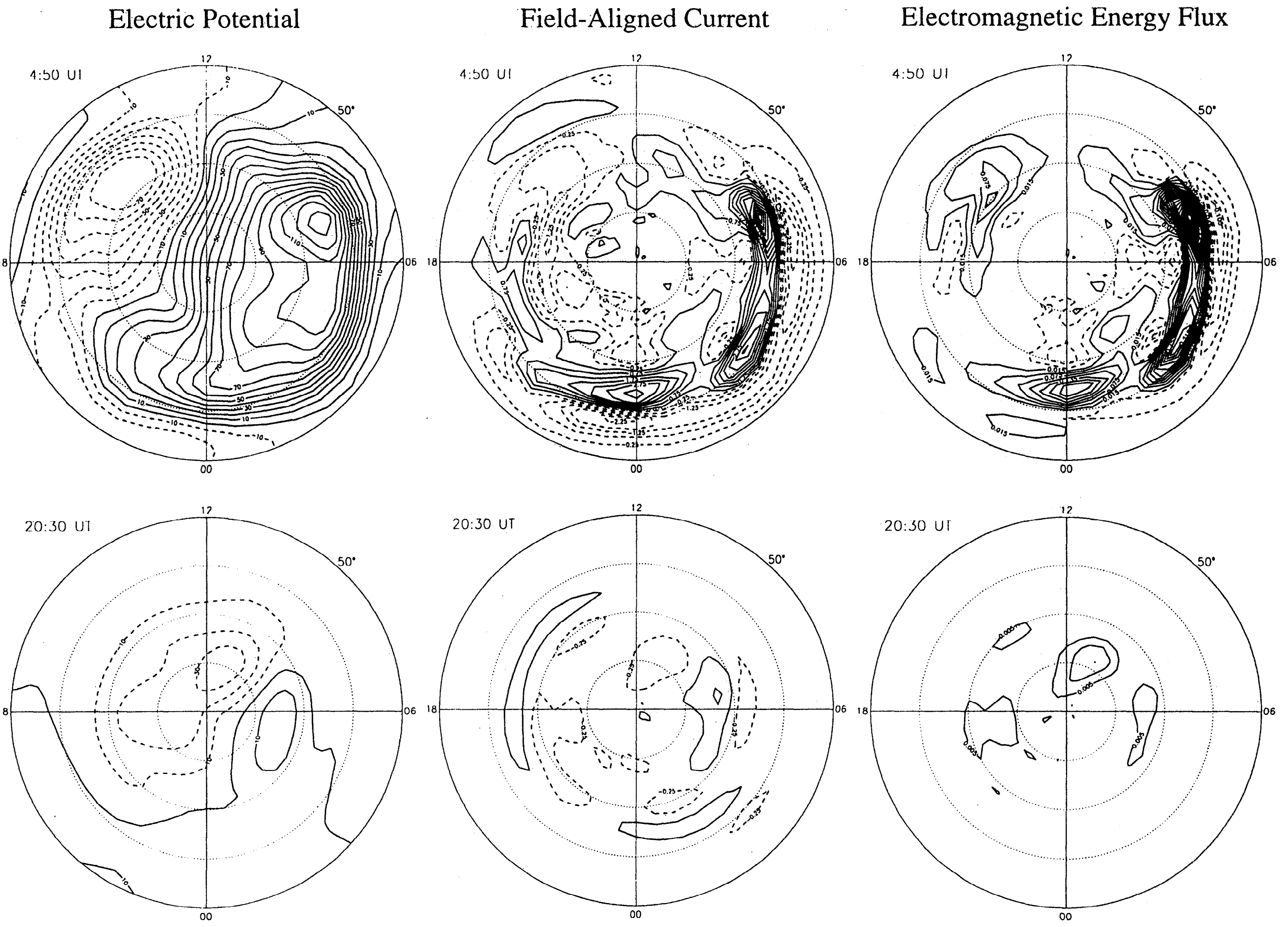

Figure 1. AMIE maps of the electric potential, field-aligned current, and upward electromagnetic (Poynting) energy flux. Dashed contours correspond to negative values. Both the field-aligned currents and the electromagnetic energy flux are taken to be positive if they flow parallel to the field. Thus, dashed contours correspond to current and energy flowing out of the ionosphere.

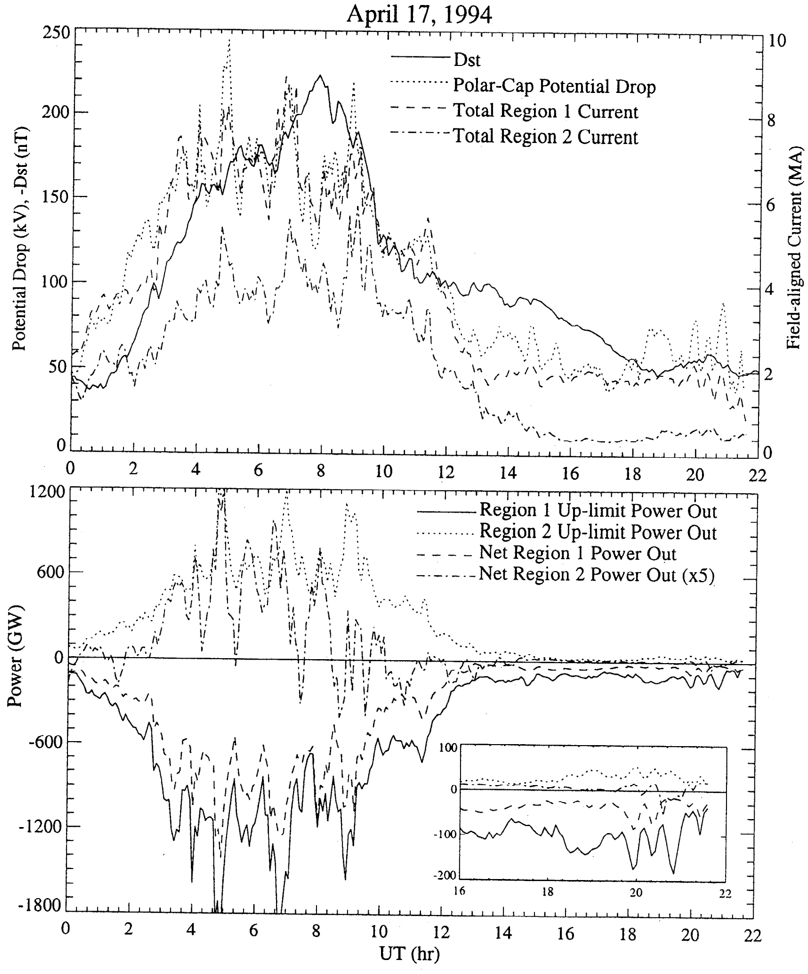

Figure 2. Electrodynamic parameters for the storm of April 17, 1994. (Top) Dst and AMIE-derived values for the polar cap potential drop and total regions 1 and 2 currents. (Bottom) AMIE-derived upper limits and actual values for the total power (Poynting flux) out of the ionosphere carried by the regions 1 and 2 current systems. The inset is a blowup of the last 6 hours.

that observed region 2 currents (as AMIE computes them) share at least this property with Vasyliunas currents, both can carry energy out of the ionosphere. Let us pursue the comparison further.

Net outward Vasyliunas currents arise when the plasma sheet encroaches deeper into the region 2 domain (to give a positive $\partial N/\partial t$ there). As was stressed in the earlier sections, such encroachment occurs when the transpolar potential drop increases, which makes the transpolar potential drop a proxy for monitoring plasma sheet encroachment. Another proxy is Dst. According to the standard storm model, the storm main phase as measured by Dst marks a time of plasma sheet encroachment, which results in ring current buildup. (To make a positive proxy, the figure plots -Dst.) The transpolar potential drop and -Dst rise together between 0000 UT and 0500 UT, then they level off for about 2 hours, after which -Dst has a secondary peak and the transpolar potential drop perhaps begins its decline, though a secondary peak between 0800 UT and 0900 UT delays the real decline till after 0900 UT. Then both proxies fall rapidly together. By 1300 UT, the transpolar potential drop is nearly back to the same value as prior to the storm and Dst is in late recovery phase.

Qualitatively, the region 2 power curve reacts to the proxy plasma sheet incursion curves the way we would expect it to if region 2 currents are Vasyliunas currents. Power flows out of the ionosphere from 0300 UT till about 0900 UT, which is the interval during which the transpolar potential drop and -Dst rise to mark the main phase then change slowly at the peak of the main phase. The smoothed power-out curve peaks around or before 0600 UT, with the transpolar potential, then it declines to an average of zero around 0900 UT. The expectation for Vasyliunas currents is that power should flow out of the ionosphere when the transpolar potential and -Dst rise. Energy can also flow out when these proxy parameters are steady if charge exchange is significant, as it might be at the peak of the main phase. Thus, the observed behavior of region 2 currents (upward energy flow coincides with increases in transpolar potential drop and -Dst and with the peak of the main phase) is consistent with the predicted behavior of Vasyliunas currents and (as far as we know) with no other current mechanism.

Immediately after the peak in the main phase, the interpretation within the standard MIC theory of what happens is complicated because the two mechanisms that cooperate to make energy flow out of the ionosphere during the main phase (plasma sheet incursion and charge exchange) now act against each other. The plasma sheet retreats under an induced reversed convection [see *Wolf et al.*, 1997], which according to (3) reverses the sign of power flow [also *Siscoe,* 1982] while charge exchange continues to drain energy out of the ionosphere. In this case the figure shows that the opposing tendencies apparently nearly cancel each other after about 0900 UT.

But later in the recovery phase, after charge exchange has become negligible and a quasi-steady state condition has set in, the situation simplifies and allows us to test the prediction that the standard MIC theory makes for steady state conditions in the absence of charge exchange: very little power carried by region 2 currents compared to the upper limit possible. The inset in the figure shows a blowup of this later time interval. We see that the power carried by region 2 currents is now about 1/30 of the possible upper limit, while the region 1 currents still carry power comparable to the possible upper limit. This is certainly consistent with the standard MIC theory and shows that region 2 currents do not conform to Sugiura's generalization of the behavior of field-aligned currents. Sugiura's generalization is obeyed, however, by the region 1 currents even in this situation. In the same manner as Vasyliunas currents, therefore, region 2 currents behave differently than region 1 currents in steady state as well as in time-dependent conditions.

These differences can be visualized using synoptic AMIE maps of electrodynamic elements as we come back now to Figure 1. The top panel gives AMIE maps of electrical potential, field-aligned currents, and upward Poynting flux at 0400 UT, which is about the middle of the main phase when plasma sheet encroachment, as monitored by the proxy variables (transpolar potential drop and -Dst) is well advanced, and net power carried by the region 2 currents, as shown in Figure 2, is flowing out of the ionosphere. The map of electrical potential shows the familiar two-cell convection pattern with about a 200 kV transpolar potential drop. The adjacent, field-aligned current pattern shows distinct region 1 and region 2 currents. There are also substorm currents in the midnight sector, which we have excluded from the current and energy tallies shown in Figure 2. The pattern of electromagnetic energy flux shows areas, associated with the region 1 currents, where intense fluxes of energy flow into the ionosphere, as expected. The unexpected features, diagnostic of the standard MIC theory, are the areas, associated with the region 2 currents, where weaker fluxes of energy flow out of the ionosphere.

There are two important geometrical alignments to note between the potential pattern and field-aligned current pattern: (1) The region 1 currents lie near the centers of the potential cells, which is why the power they carry into the ionosphere (for this is the sense of energy flow appropriate to their polarity) is nearly the upper limit given by the total region 1 current times the total transpolar potential drop; and (2) the region 2 currents lie within the same set of closed potential contours as the proximal region 1 currents, which is why they carry energy in the opposite direction as the region 1 currents, namely, out of the ionosphere. Since the region 2 currents are farther than the region 1 currents from the centers of the cells where the potentials peak, the power they carry is considerably less than the upper limit given by the total region 2 current times the transpolar potential drop (in this case, about a factor of 5 less).

The difference between the time-dependent situation and the steady state situation for region 2 currents can already be sensed from the top panel of Figure 1. Region 2 currents necessarily lie relatively far from the peaks in the electrical potential, since the region 1 currents lie in between. So it is hard for region 2 currents to deliver much power under any circumstance. Circumstances favor region 2 acting as a net power source to the magnetosphere, however, when the transpolar potential drop increases, thereby expanding the size of the convection cells so that the sites of region 2 currents lie well within the cells, that is, so that the potential drop between the foci of the region 2 contours is significant. After an expansion of the potential pattern following an increase in the transpolar potential, the pattern automatically contracts as the shielding electric field associated with the earthward motion of the plasma sheet builds up [*Siscoe*, 1982]. This contraction moves the region 2 sites again to the periphery of the potential pattern, that is, to where the potential difference between the foci is small. In true steady state, the average potential difference goes to zero. Since the net power that the region 2 currents carry is the total region 2 current times the average potential difference between the two region 2 foci, the net power gets small as the potential difference gets small. This is a restatement of the prediction of the standard MIC theory.

We see the steady state condition just described in the bottom panel of Figure 1. It shows the electrodynamic patterns for 2030 UT. First, locate the two region 2 contours in the second frame of the panel. Then note from the potential contours in the first frame that the contour of zero potential touches both region 2 contours, telling us that both contours are at about the same potential. This is the condition for small net power transport, as seen in the third frame and in the inset in Figure 2.

This observation completes the tests of the standard theory of region 2 currents. The theory is consistent with properties of region 2 currents that are different than properties of region 1 currents, and as far as we know, no other theory is consistent with these specifically region 2 properties. Before concluding, we note the implications of the AMIE results regarding the role of region 2 currents as power providers for magnetospheric dynamics.

6. A Remark on the Role of the Power Carried by Region 2 Currents

We have seen that the region 2 currents are a source of power to the magnetosphere during the storm main phase. This raises the question, can the region 2 currents be a significant contributor to the power needed to create the main phase? If we use the Dessler-Parker formula to compute a lower limit on the required energy, this example answers, no. *Dessler and Parker* [1959] derived a formula useful for estimating the energy associated with the main phase of a magnetic storm as measured by Dst. If Dst results from a symmetric ring current on dipolar field lines (and the contribution of ground currents is included), their formula applies. It says that one needs 300 GW to produce a 100 nT drop in Dst in 3 hours, which is about what this storm achieved. Here 300 GW is a lower limit since it also takes energy to distort the magnetic field and since charge exchange hides from Dst some of the energy that actually gets consumed in building up the ring current. During the growth of the main phase for our April 17 storm, the average power carried up by region 2 currents is less than 100 GW. The difference between what is required and what the region 2 currents delivered considerably exceeds a factor of 3. Evidently, as we have seen already in Rice Convection Model (RCM) simulations [*Wolf et al.*, 1997], the main source of power for the ring current is the cross-tail potential times the cross-tail current. If so, there is apparently a division of effort wherein the tail currents do the heavy duty transport of the plasma sheet while the region 2 currents guide and adjust its earthward boundary.

7. Conclusions

The standard MIC theory for region 2 currents makes the following predictions relating to energy flow between the ionosphere and the magnetosphere:

1. In quasi-steady state with no significant charge exchange, region 2 currents transfer energy between the ionosphere and the magnetosphere at a rate small compared to the theoretical maximum rate given by the total region 2 current in amperes times the transpolar potential drop in volts.

2. During times of plasma sheet incursions into the inner magnetosphere (corresponding to an increase in the transpolar potential drop), region 2 currents transfer energy out of the ionosphere into the inner magnetosphere at a rate that can approach the same order of magnitude as the theoretical maximum rate. (The reverse also happens: When the plasma sheet retreats from the inner magnetosphere--corresponding to a decrease in the transpolar potential drop--region 2 currents transfer energy from the inner magnetosphere into the ionosphere. This case is perhaps not as interesting for the present discussion, since it predicts the expected direction of energy flow. It is interesting, however, in discussions of ring current energy budgets, since it represents a way to weaken the ring current that does not involve charge exchange or particle precipitation.)

3. Charge exchange acts to extract energy from the ionosphere via region 2 currents.

These predicted properties are distinctly different than the observed and theoretically expected properties of region 1 currents. They are therefore diagnostic of the standard MIC theory of region 2 currents.

An AMIE analysis of the April 17, 1994, magnetic storm confirms the prediction that region 2 currents transfer energy out of the ionosphere during times of earthward plasma sheet encroachment. It also confirms the prediction, albeit with smaller signal to noise ratio, that region 2 currents transfer negligible energy when conditions are quasi-steady state with no significant charge exchange. The analysis is also consistent with the prediction that charge exchange extracts energy from the ionosphere via region 2 currents. Without independent charge exchange data, however, we may only claim that the analysis is consistent with the prediction, not that it confirms the prediction.

For the storm studied, the energy transferred during the main phase to the inner magnetosphere by region 2 currents contributed a minor part of the energy needed to create the main phase.

Appendix: Derivation of the Vasyliunas Pseudo-Hall Current Equation

This derivation follows *Vasyliunas* [1972]. Below, all quantities are referred to and are evaluated on the ionospheric surface. We take the plasma sheet plasma within the region 2 domain to consist of hot ions and cold electrons, where hot and cold mean significant or negligible thermal drift compared to electric field drift. Let $\vec{I}_m$ be the total magnetospheric current in a magnetic flux tube of unit area in the ionosphere. Then

$$\vec{I}_m = eN(\vec{V}_B + \vec{V}_D) - eN\vec{V}_B + \vec{I}_M \qquad \text{(A1)}$$

where N is the flux tube content of energetic ions, $\vec{V}_B$ ($= \vec{E} \times \vec{B} / B^2$) is the electric field drift, V_D is the thermal drift (gradient and curvature), and I_M is magnetization current. The equation incorporates charge neutrality, such that there are also N electrons which *ExB* drift with the ions. (Note that the low energy ions, which are there as a background or arise from charge exchange, have negligible thermal drift. Therefore, they do not appear in this equation, since they merely *ExB* drift along with their charge-neutralizing electrons.) We need also the continuity equation for hot ions,

$$\partial N / \partial t + \nabla \cdot N(\vec{V}_B + \vec{V}_D) = -L_{ex} \qquad \text{(A2)}$$

where L_{ex} is the charge exchange loss rate. Now the current density out of the ionosphere is

$$J_z = \nabla \cdot \vec{I}_m \qquad \text{(A3)}$$

Combine (A1-A3) and note that magnetization currents are divergenceless to arrive at

$$J_z = -\nabla \cdot eN\vec{V}_B - e\partial N / \partial t - eL_{ex} \qquad \text{(A4)}$$

It is now a simple matter to go from (A4) to (1) with $\Sigma_H{}^* = eN/B$.

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G. Lu, High Altitude Observatory, National Center for Atmospheric Research, POB 3000, Boulder, CO 80307.

G. L. Siscoe, Center for Space Physics, Boston University, 725 Commonwealth Avenue, Boston, MA 02215. (e-mail: siscoe@buasta.bu.edu)

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