DIALOG ON THE RELATIVE ROLES OF RECONNECTION AND THE "VISCOUS" INTERACTION IN PROVIDING SOLAR-WIND ENERGY TO THE MAGNETOSPHERE

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INTRODUCTION BY PANEL CHAIR: G. ROSTOKER

It has long been known that the solar wind must supply energy at the rate of $\sim 10^{10}$ to 10^{12} J/s to the magnetosphere in order to account for energy dissipated in the auroral oval through particle collisional processes and the energy required for ring current formation. In 1961, two methods were independently proposed by which the energy could enter the magnetosphere. Axford and Hines[1] contended that viscous processes at the earth's magnetopause could lead to energization of the magnetized plasma in the interior of the magnetosphere. Their primary interest was in studying the implications of the ensuing convective motion of the plasma and, as a consequence, they did not explore the possible physical mechanisms through which such a viscous behaviour might arise at that time. In the same year, Dungey[2] suggested that the interconnection of the IMF with the earth's magnetic field could permit a reconfiguration of the magnetosphere with the development of a long magnetic tail. One crucial prediction of Dungey's theory was that the entry of solar-wind energy would be modulated by the magnitude and direction of the component of the IMF parallel (antiparallel) to the earth's magnetic field lines at the dayside magnetopause. This type of dependency was confirmed by the late 1960s (Fairfield and Cahill;[3] Rostoker and Fälthammar[4]) and, coupled with the strong theoretical base developed for the reconnection hypothesis (Petschek;[5] Yeh and Axford[6]), further consideration of the viscous interaction was set aside. Despite the theoretical study of diffusive processes by Eviator and Wolf[7] and observation evidence by Freeman et al.[8] suggesting that viscous processes might be of importance, the last word for a decade seems to have gone to Axford[9] who stated:

> "However, although there are a few observations suggesting that the viscous effect could be important (e.g., Freeman et al., 1968), it seems unlikely that we would be so unlucky to have two competing mechanisms of equal significance. For the present, we will abandon the simple form of viscosity (i.e., momentum transfer without field-line reconnection) and concentrate on field-line reconnection as a means of exerting a shear stress on the body of the magnetosphere."

By the early 1970s, aided by the application of plausible physical processes to a comprehensive phenomenological model of reconnection processes by Coroniti and Kennel,[10] the Dungey hypothesis dominated thinking regarding the nature of the solar terrestrial interaction.

In the mid-1970s, a new set of observations came to light that led to a revival of the viscous interaction as a process that might have to be reckoned with. The discovery of the low-latitude boundary layer (LLBL) by Eastman et al.[11] provided evidence for a plasma population at low GSM latitudes just inside the magnetopause whose estimated particle number flux of $\sim 10^{26}$ to 10^{27}/s was adequate to populate the magnetotail and whose momentum flux ($v \simeq 150$ km/s) was large enough to make it of consequence in terms of the energetics of the solar terrestrial interaction. Subsequent studies by Lundin and Dubinen[12] and by Eastman et al.[13] provided more support for the view that this viscous interaction could not be ignored and the observations of "viscous cells" at ionospheric levels reported by Reiff[14] make it clear that the viscous interaction influences ionospheric processes.

The question then arises as to how significant a role viscous processes play. While Cowley[15] discounts their importance totally, based on the results of Wygant et al.[16] and Mozer,[17] several theoreticians have put forward mechanisms that suggest a more significant role for viscous processes. Two types of mechanisms under consideration are gradient drift entry[18] and impulsive "plasmoid" entry for which different mechanisms have been proposed by Heikkila[19] and Lemaire.[20] One of the most promising theoretical approaches is that of Miura[21] who considers the Kelvin-Helmholtz instability on the magnetopause as a mechanism for anomalous momentum transport that can provide up to 30 kV across the magnetotail.

At present, it seems probable that magnetic field-line reconnection is the dominant means by which solar-wind energy enters the magnetosphere (after which it is stored in the magnetotail and ultimately unloaded to power substorm expansive phase activity). The question is, how important is the role of the viscous interaction that seems to be responsible for the LLBL. A specific question that might be asked is how much of the (slowly varying) directly driven system[22] activity can be accounted for by a viscous interaction.

COMMENTS FROM PANEL MEMBERS

D. N. Baker

It is probably a fair assessment of nature to say that if a given physical process can occur, it will. I certainly feel this way about "viscous" interaction processes in solar-wind/magnetosphere coupling. However, the specific charge to this panel was to determine the relative importance of the two modes of interaction. The following are my impressions based on experimental results in the distant ($r > 100\ R_e$) magnetotail.

I feel that the competition between viscous and reconnection processes in magnetotail formation is difficult to assess and quantify in a very precise way. From my own observational perspective, however, it appears that reconnection processes are of overwhelming importance in the distant magnetotail, with the tail owing its very existence and basic structure primarily to dayside reconnection and its consequences.

As shown by Gosling et al.,[23,24] the ISEE 3 data reveal broad plasma boundary layers immediately inside the distant tail magnetopause. As pointed out in those papers, the presence of such boundary layers at great tail distances shows very strongly that plasma from the magnetosheath often crosses the magnetopause locally along much of the tail length, implying that the tail is "open." This in turn implies that reconnection has taken place between solar wind and magnetospheric field lines to produce those effects. In examining asymmetries between the distant lobes (north and south), Gosling et al.[24] often found density differences of factors of 3–10. The density effects show dawn-dusk asymmetries that depend on the IMF (e.g., high density in the north-dawnside lobe for $+B_y$ etc.) that also strongly support a "reconnection" interpretation of the distant tail character.

These impressions have been further reinforced by the examination of higher energy electrons that serve as a kind of "test particle" population.[25,26] It is found that electrons in the 50–500 eV energy range commonly exhibit strong, field-aligned anisotropies in the tail lobes. Because of large tail motions, the ISEE 3 data provide extensive sampling of both the north and south lobes in rapid succession. The bidirectional fluxes are found to occur predominantly in the lobe directly connected to the sunward IMF in the open magnetosphere model (north lobe for away sectors and south lobe for toward sectors). Electron anisotropy and magnetic field data are presented that show the transition from unidirectional (sheath) electron populations to bidirectional (lobe) populations. Taken together, the evidence suggests that the bidirectional electrons that are observed in the distant tail are closely related to the polar rain electrons observed previously at lower altitudes. Furthermore, these data provide strong evidence that the distant tail is comprised largely of open magnetic field lines in strong distinction to some recently advanced models[27] that postulate a much larger role for viscous tail formation processes.

Finally, strong and, indeed, accelerating plasma flow observed as one goes deeper down the tail suggests an important role for magnetic reconnection at a distant nightside neutral line.[28,29] Viscous processes may play some role in the low-latitude boundary layers adjacent to the distant-tail magnetopause,[30] but for the vast majority of the distant-tail volume it seems probable that reconnection processes have been the important agents of the tail structure and development.

J. Lemaire

The question addressed in the following paragraph is, "How much can we rely on quasistationary (i.e., quasisteady state) models to describe the interaction between the solar wind and the earth's magnetic field?" An equivalent question is, "How much can we rely on quasistationary convection flow patterns, quasistationary electric equipotential contours and current systems deduced from the steady-state reconnection or viscous-like interaction models?"

Most of the time the answer to these questions will be, "Not very much!" Indeed, most of the time the solar wind is a very inhomogeneous medium. The solar-wind plasma impinging on the geomagnetic field is almost always nonuniform over distances smaller than the dimensions of the magnetosphere.

To convince oneself that the supersonic solar-wind plasma is generally not uniform over the surface of the magnetopause, it suffices to examine high-resolution magnetograms of the IMF. From these high-resolution magnetograms it can be seen that it is sometimes hard to find periods of time larger than half a minute during which the three components of the solar-wind magnetic field are strictly constant.

Even in the so-called quiet solar wind, when the plasma bulk velocity (V) is low, it is difficult to identify extended periods of time, Δt, when high-resolution IMF magnetograms are perfectly flat, i.e., when the solar wind was uniform over a distance Δx ($= V\Delta t$) exceeding 20 R_e or the length of the magnetotail. When the magnetic-field components are averaged over 15 seconds (or over 1 hour of time) these small-scale variations and nonuniformities are washed out and are easily overlooked.

The same can be said for solar-wind plasma observations that are generally sampled at a rate much lower than spacecraft spin frequency. Therefore, these low time resolution plasma measurements were inadequate to identify small-scale plasma and field irregularities in the solar wind. Nevertheless, these plasma irregularities are present in the solar wind; they even became steep and compressed when they transit through the bow shock before they hit the magnetopause surface.

As a consequence, except for very rare periods of time when the solar wind is strictly constant for more than several minutes, the interaction between the solar-wind plasma and the geomagnetic field cannot be described in the framework of any steady-state theory. Most of the time steady-state reconnection or viscous-like interaction models are invalid representations of the actual magnetosphere because they are based on the simplifying assumption that the external boundary conditions are time independent. The rapidly changing boundary conditions at the surface of the magnetosphere induce time-dependent electric and magnetic fields inside the magnetosphere. The effects of these rapidly changing electromagnetic fields on magnetospheric and ionospheric plasma are commonly ignored. These electromagnetic field effects cannot be understood nor modeled in terms of slowly varying electrostatic or magnetostatic field distributions; they are electrodynamic effects generated by AC electric fields that cannot be understood in the framework of DC electric-field theory.

There are a number of conflicting observations that can only be explained with time-dependent models—the most obvious example of such electromagnetic fields being the irregular short-time-scale fluctuations that are almost always present in magnetospheric electric and magnetic field observations. These ultra-low-frequency field fluctuations are superimposed on the larger scale variations usually studied in the steady approximations.

It cannot even be argued that the magnetosphere could be described in terms of a composite model that would have attributes partly of both the reconnection (open) and the viscous-like (closed) steady-state models. Indeed, in such a composite steady-state magnetosphere model any of the anticipated electrodynamic effects (e.g., the observed rapid field fluctuations) expected from AC boundary conditions are still missing and overlooked.

The rapidly changing boundary conditions at the surface of the magnetopause induce transient magnetic fields and electric field perturbations inside the magnetosphere. This leads to transient and patchy opening (or interconnection) of magnetic field lines as in stationary reconnection pictures. But this leads also to antisunward drag of magnetospheric plasma along the flanks of the plasma boundary layer as in the viscous-like interaction models. This means that time-dependent interaction models are not only imposed on us by the nonuniform nature of the solar-wind flow but will be able to reconcile otherwise conflicting observations.

Therefore, instead of asking if reconnection is more likely than viscous-like interaction or vice versa (assuming we all would agree on a nonequivocal and undisputed definition of these two words), we should first ask the question, "Is the solar-wind interaction with the magnetosphere a steady-state or a dynamical one;" "Or can we always interpret our observations in terms of steady-state magnetospheric models with closed electric equipotential contours and stationary magnetic field line distributions?" The answer is, "No, most of the time we cannot."

Therefore, it is speculative to draw definite conclusions in favor of one or another of the many existing reconnection or viscous-like interaction models without verifying beforehand (for instance, from high-resolution IMF magnetograms) that the solar-wind field and plasma impinging on the magnetosphere have been uniform and stationary for a long enough period of time preceding the observations used to draw these conclusions. Otherwise, these conclusions may most probably be meaningless.

G. Rostoker

It is quite apparent, at this time, that at least two distinctive processes operate at the magnetopause so that energy and/or momentum penetrates into the magnetosphere from the solar wind. One of these processes involves the creation of a class of magnetic field lines with one foot on the earth and one foot on the sun. This process is modulated by the magnitude and direction of the IMF and is moderately well predicted by a theory whose physical process is termed reconnection. Such a process must take place, if one is to accept Faraday's law (cf. Ref. 31). The evidence for reconnection in a magnetospheric context seems indisputable.

On the other hand, observations of regions adjacent to the magnetospheric equatorial plane and just inside the magnetopause reveal the presence of antiearthward flowing plasma on closed field lines whose existence is not accounted for by reconnection theory.[11] The existence of this low latitude boundary layer (LLBL) has been attributed to some type of viscous interaction at the magnetopause and the estimated electric fields ($\sim$1–3 mV/m) and total particle fluxes ($\sim 5 \times 10^{26}$/s) are sufficiently large to warrant attention. Physical mechanisms (e.g., anomalous momentum transport as enunciated by Miura[21]) do exist to account for the observed particle populations of the boundary layers (both LLBL and plasma mantle). The real question then lies in the relative contributions of reconnection and "viscous" processes for varying levels of magnetospheric activity.

In this respect, it has been traditional to ignore the possible effects of "viscous" processes since observations (e.g., see Refs. 15 and 15) seem to indicate a total contribution of no more than $\sim$20 kV to the cross-polar cap (CPC) potential drop due to nonreconnection processes. This conclusion is based on the observation that during episodes of northward IMF, a CPC potential drop of $\sim$20 kV exists independent of the magnitude of the IMF B_z component. The increase in the CPC potential drop with increasing magnitude of southward IMF B_z is attributed solely to reconnection. While such a modulation is well predicted by reconnection theory, what is not clear at this time is whether or not viscous processes are also modulated by the IMF B_z component. If such a modulation occurs, the "viscous" interaction might, in fact, mimic the reconnection process in terms of magnetospheric response. For example, in the Miura[21] concept of anomalous momentum transport involving the Kelvin-Helmholtz instability, it seems inconceivable that magnetic shear across the velocity shear zone would not alter the efficiency of the momentum transport. It is incumbent on the reconnection supporters to demonstrate that viscous processes either do not depend on IMF orientation or that the dependence does not follow the observations. Only if this "rule out" procedure is followed will it be demonstrated unequivocally that the reconnection process is dominant at all times in the solar terrestrial interaction.

V. M. Vasyliunas

In my view, the so-called "viscous" processes do not play any significant role in magnetotail formation. I arrive at this conclusion by an extension of the global stress balance arguments due primarily to George Siscoe (see Ref. 32 and references therein). Calculate F_x, the solar magnetospheric x component of the total force on the magnetotail, by integrating the stress tensor over a closed surface surrounding the magnetotail, a surface that I choose to extend to just outside the magnetopause and its boundary layers on the flanks (whereas in most earlier treatments the surface had been chosen just inside). F_x, which by Siscoe's well-known argument must vanish, is then given by

$$F_x = -(B_T^2/8\pi)A_T(1 - \delta) + S\Delta V_x = 0 \quad (1)$$

where the first term is the net stress of the highly stretched-out magnetic field B_T over the cross-sectional area A_T of the near-earth face of the magnetotail, reduced by plasma pressure effects δ, and the last term is the inertial stress of the total mass flow S of plasma through the magnetotail and the region of its interaction with the solar wind, the plasma undergoing an average change of velocity ΔV_x. The term δ arises primarily from pressure on the flanks of the flaring magnetotail and to a lesser extent from the plasma sheet; I estimate $\delta \approx 0.7$ from conventional models.

Equation 1 states that about ⅓ of the magnetic stress of the magnetotail must be balanced by the loss of momentum of plasma flow interacting with it. An interior stress balance is of course possible with pressure gradients (e.g., Ref. 33), but the magnetotail is ultimately formed as the result of solar-wind flow—otherwise it would not be aligned with it!—and must be maintained by an exterior stress balance (the integration surface to compute F_x was chosen precisely to tap these inertial stresses).

To test whether a proposed process is adequate to maintain the magnetotail, I estimate S, calculate from Eq. 1 the implied ΔV_x, and ask whether its value is reasonable. In all cases, S turns out to be large compared to the net input of solar-wind plasma to the magnetosphere. Hence, most of the plasma in S must be assumed to flow out again, which in turn implies that ΔV_x must be small compared to the average inflow speed V:

$$\Delta V_x / V \ll 1 \quad (2)$$

For a reconnection process, S is given by plasma inflow along open magnetic field lines. In an obvious notation,

$$S = \int dA\ \rho V_n = \int dA\ \rho B_n/(4\pi\rho)^{1/2} \quad (3)$$

and the total open magnetic flux is

$$\int dA\ B_n = B_T A_T \quad (4)$$

hence, from Eqs. 1, 3, and 4,

$$\Delta V_x / V \simeq [(1 - \delta)/\sqrt{2}\ ]\ [B_T^2/8\pi\rho V^2]^{1/2} \quad (5)$$

where ρ and V are average values in the inflow region comparable in this case to the solar-wind values ρ_{SW} and V_{SW}. From the observed values,

$$B_T^2/8\pi\rho_{SW}^2 \approx 0.1$$

and thus the reconnection process can maintain the magnetotail provided that

$$\Delta V_x / V \approx 0.07$$

which is consistent with Eq. 2.

For a viscous process, on the other hand, the mass flow S is provided by the magnetopause boundary layers, with $h \simeq 1\ R_e$ the layer thickness and $R_T \simeq 20\ R_e$, the tail radius at the near-earth edge of the magnetotail,

$$S = \int dA\ \rho V_n \approx 2\pi\ R_T\ h\ \rho V \quad (6)$$

and, from Eqs. 1 and 6,

$$\Delta V_x / V = [(1 - \delta)/2]\ [B_T^2/8\pi\rho V^2]\ [R_t/h] \quad (7)$$

In this case $\rho < \rho_{SW}$ and $V \leq V_{SW}/2$, approximately. Then the condition that the magnetopause boundary layer flow be able to maintain the magnetotail is

$$\Delta V_x / V \gtrsim 1.2$$

which is markedly inconsistent with Eq. 2.

It appears that the magnetospheric boundary layers (in contrast to the inflow implied by reconnection) simply do not carry enough momentum to build up the magnetic stress of the magnetotail, unless one supposes that their flow is completely stopped or reversed. But then S would represent a net mass input into the magnetosphere, and the value given by Eq. 6 implies

$$S/\rho_{SW} V_{SW} A_T \approx 0.02$$

which is too large by an order of magnitude. I conclude that, whatever other role "viscous" processes might have in the magnetosphere, if they lead to the boundary layers that are observed, they do not contribute significantly to the formation of the magnetotail.

SUMMARY: G. ROSTOKER

The views of the panel members were, as could be expected, rather diverse. Axford and Vasyliunas used analytical expressions based on the physics of the plasma processes involved to argue that "viscous" processes could not account for the energy flow required to power storms (Axford) or for the balance between the magnetic stress of the magnetotail and the loss of momentum of plasma flow interacting with the tail (Vasyliunas). Baker supported this viewpoint based on observations of the deep tail particle and field behavior obtained using the ISEE 3 satellite. On the other hand, Lundin[12] argued that the very existence of the low-latitude boundary layer provided one with a source of particles that was quite adequate to supply the plasma sheet and potential drops whose implications for high-latitude convection and electric current flow are non-trivial.

Lemaire took a somewhat different viewpoint, arguing that any steady-state assumptions made in assessing either reconnection or "viscous" processes are invalid because the solar wind represents a rapidly time-varying environment to which the magnetosphere is continuously exposed. (This concern was voiced at an earlier Chapman Conference on Solar-Wind/Magnetosphere Coupling by G. Rostoker (see Ref. 34) who noted that the IMF B_z component fluctuates on a characteristic time scale far shorter than the impulse response time of the magnetosphere.) Lemaire's viewpoint is shared by Heikkila[19] and there is evidently a question (which deserves to be addressed further) as to how valid it is to apply steady-state analytical formalisms to a situation where time-varying conditions are the norm.

In this dialog, while the existence of both "viscous" and reconnection effects was acknowledged, the question of the relative roles of the two processes was really not answered. Axford's demand that

$$\left(\frac{\rho \nu v}{\delta}\right) (v\, A) \sim 10^{19} \text{ ergs/s}$$

(where $(\rho \nu v/\delta)$ is the viscous stress, v the magnetosheath velocity, and A the area of the surface across which the interaction takes place) and his contention that the "viscous" effects could not achieve this only proved that, by themselves, "viscous" effects were inadequate. In addition, the demand that 10^{19} ergs/s be supplied amounts to storm conditions where it appears certain that reconnection processes play an important role. The reader is tempted to ask how easily a demand of 10^{17}–10^{18} ergs/s (typical of average activity levels) could be met with "viscous" processes playing a more significant role proportionately. Vasyliunas' claim that the stress balance in the tail rules out a consequential role for "viscous" effects was a very instructive exercise in which he argued that the total mass flow $\Delta M/\Delta t$ through the magnetotail, calculated from

$$\frac{\Delta M}{\Delta t} = \frac{1}{3}\left(\frac{B_T^2}{8\pi}\right)\frac{A_T}{\Delta v_x}$$

is large compared to the net input of solar-wind plasma to the magnetosphere. He concludes that very little solar-wind flow energy is transferred to the magnetosphere (viz., $\Delta v_x/V_{sw} \ll 1$) and thus reconnection must be the dominant contributor to the global stress balance. What the balance might be between reconnection and "viscous" effects was not really spelled out quantitatively particularly as regard to how large a tail could be supported by "viscous" effects alone. One problem here is the varying estimates of $\Delta M/\Delta t$ stemming from early LLBL studies that seem to range from 10^{26}–10^{27}/s (Eastman, private communication). (For example, Heikkila often quotes particle fluxes of $\sim 10^{27}$/s for the LLBL contribution. For a change in boundary-layer velocity from ~ 200 km/s at the magnetopause to zero at the LLBL/CPS interface and $R_T = 15\ R_e$ with $B_T = 10$ nT, the stress balance equation of Vasyliunas is satisfied.) It will be incumbent on LLBL researchers to provide the community with a more thorough study of the mass fluxes in this important region of space if we are to be able to define accurately their relative roles in powering magnetospheric activity. Perhaps Baker best summarized the situation in noting that "... if a given physical process can occur, it will." The existence of the LLBL tells us that a process other than reconnection is at work. Establishing how that process is modulated by the interplanetary particle and field environment will go a long way in quantitatively assessing its impact on magnetospheric activity levels.

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