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REPLY

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Berthelier [1989] claims that Russell [1989] does not prove that the McIntosh effect is not efficient in producing the semi-annual variation and the diurnal variation. In support of the McIntosh hypothesis [McIntosh, 1959], she notes that her model [Berthelier, 1976] of the Russell-McPherron [1973] mechanism did not reproduce the semi-annual variation seen in 1964-1969, and that within statistical error the phase of the diurnal variation obtained by Russell [1989] is not different from that predicted by the McIntosh hypothesis. We disagree with her conclusions on four grounds. First, the observational study [Berthelier, 1976] with which she compares her model is seriously flawed. We were careful to avoid these problems in our 1989 study. Second, the model used in her 1976 study does not correctly model the dependence of geomagnetic activity on the southward component of the IMF. The amplitude of the semi-annual variation can be predicted by the Russell-McPherron mechanism with this dependence correctly modeled. In contrast, the McIntosh effect or Kelvin-Helmholtz model makes no predictions of amplitudes. Third, the phase of the diurnal variation is significantly different than that predicted by the McIntosh effect [1959]. Lastly, the diurnal variation, attributed to the McIntosh effect, appears to be sensitive to the north-south component of the interplanetary magnetic field, a result not expected if this variation were due to the Kelvin-Helmholtz instability.

Determining the Interplanetary Magnetic Field

The studies of Russell [1989] and Berthelier [1976] differed importantly in their determination of the interplanetary magnetic field. Russell [1989] used 3-hour intevals with 90% or more of the interval covered by IMP-8 measurements. These were all obtained in the solar wind in earth orbit. Berthelier [1989] claims that the study of Berthelier [1976] used "17520 three-hour intervals sorted according to the daily dominant polarity". There are 2 problems with this determination of polarity. First, the polarity during any 3-hour period may be different than the dominant daily polarity. Secondly, in the period of her study, the dominant polarity of the IMF was not known for all 17520 three-hour intervals. Reference to her original sources [Wilcox and Colburn, 1969; 1970; 1972] reveals many missing days when the earth orbiting satellites were in the magnetosphere and even more seriously that very large sections of the six year interval were not covered by earth orbiting spacecraft. In one case the dominant polarity was simply extrapolated (February 1964 to October 1964). In other cases interplanetary spacecraft, such as Mariner 4 to Mars (December 1964 to July 1965) and Pioneer 6 in heliocentric orbit (December 1965 to November 1966) were used. Since 17520 3-hour intervals cover the full 6 year period from 1964-1969, we must conclude that the daily dominant polarity was extrapolated for about 40% of the days. In short, the dominant polarities used by Berthelier [1976] are probably incorrect for many intervals.

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These errors could explain why she did not get as complete a separation of the semi-annual variation into 2 annual waves ordered by IMF polarity as was obtained by Russell [1989]. Figure 2 of Russell [1989] shows very clearly that any semi-annual variation of geomagnetic activity independent of the IMF polarity is quite small. The right-hand panel of Figure 1 of Berthelier [1976], which shows the AE index, also shows little semi-annual variation in the separated traces, but here the annual variation in ionospheric conductivity has removed all evidence of the semi-annual variation in the AE index. Thus we should not expect to see such variation. In contrast, the dominant polarities used by Russell [1989] have very little likelihood of error. While this latter conservatism reduced the size of the dataset used, it increased confidence in the results.

The Correct Model

Berthelier [1976] using data obtained in only the 2 years, 1967 and 1968, modeled the dependence of the Am index on the north-south component IMF with the formula

$$Am = 13.8 - 4\ B_z \qquad (B_z < 0)$$
$$Am = 13.8 + 0.2\ B_z \qquad (B_z > 0)$$

where the B_z values are one-hour averages measured in solar magnetospheric (GSM) coordinates. Russell [1989] however, pointed out that the dependence of Am on the southward component, B_s, was non-linear so that at low values of B_s the variation was much steeper

$$Am = 11.25 + 5.9\ B_s \qquad 0 \leq B_s < 2\ \text{nT}$$

Here B_s is taken to be the average southward component of IMF over the 3-hour period, setting all northward measurements equal to zero. Five minute averages were used in calculating the 3-hour B_s values. The non-linearity is clearly evident in Figure 1 of Russell [1989]. It is appropriate to adopt the slope of the curve from 0 to 2 nT, rather than higher as Berthelier did because the Am index variations which are being studied range from about 13 to 25 as shown in Figure 2 of Russell [1989]. This difference in slopes increases the efficiency of Russell-McPherron mechanism by 50% over the values calculated by Berthelier [1976]. It may also be important that Russell [1989] used medians whereas Berthelier [1976] used averages to describe the annual and daily variations. Medians are less sensitive to outliers. However, we note that the mean Am index in her study (see her Figure 1) and the median activity in our study (see the top panel of our Figure 3) are nearly identical at 17 nT

A second effect enhances the efficiency even more. As demonstrated by Russell [1989] and illustrated in his Figure 1, the Am index is dependent on the velocity of the solar wind as well as the southward component of the IMF. Thus the heliographic latitude dependence of the solar wind velocity enhances the amplitude of the semi-annual variation [Russell, 1975]. Since this effect in our model enters the problem as a product with the southward component it is not removed by subtracting the positive and negative By annual variations. Only effects independent of By would be removed by the subtraction. Inspection of the top two panels of Figure 2 of Russell [1989] shows little evidence for a semi-annual variation of Am independent of By. These two panels would show the McIntosh effect if it were present. They do not. Finally as noted by Russell [1989], the relative amplitudes of the semi-annual and diurnal variations and their absolute amplitudes are correctly predicted by the Russell-McPherron mechanism.

Summer Minus Winter Diurnal Variation

One prediction of the McIntosh effect model is that the diurnal variation for summer minus the diurnal variation for winter would be a sinusoidal variation maximizing at 0439 UT [Berthelier, 1976]. The McIntosh effect is not quantitative in the sense that it does not predict an amplitude for this effect. Russell [1989] found the phase of this variation to be such that it maximized at 0623 UT, almost 2 hours later than predicted. While this paper used all data independent of solar wind conditions in deriving this phase, the data set was still restricted to times when there were solar wind data available from IMP-8. At the suggestion of A. Berthelier, we have redone the analysis using every available Am index value from 1957 to 1987. The resulting phase is 0524 UT $\pm$ 9 minutes or only 45 minutes later than expected for an instantaneous response to any mechanism maximizing in efficacy when the dipole was perpendicular to the solar wind. The error given is the probable error of the mean calculated by analyzing the Am index over independent subintervals.

If we analyze the phase of the By dependent diurnal variation in independent intervals we obtain a phase of maximum at 1152 UT $\pm$ 18 minutes or 73 minutes after the time of the strongest expected interaction of the IMF with the magnetosphere. The sizes of both these time delays, 45 and 73 minutes are both suggestive of storage of energy in the tail. If the Kelvin-Helmholtz instability were responsible for the diurnal variation we would expect no time delay.

The Diurnal Variation for Northward IMF

Another test of the role of the Kelvin-Helmholtz instability in producing the summer-minus winter effect is to examine the diurnal variation when the IMF is northward. The Kelvin-Helmholtz instability should not be affected by the polarity of the magnetic field. We restrict our analysis to times when there was no southward IMF during the 3-hour period, i.e., $B_s = 0$. While this limits the size of our data sample to only 60 3-hour intervals, it ensures that reconnection on the dayside magnetopause, which is thought to be the cause of geomagnetic activity in the Russell-McPherron model, does not recur. For northward IMF the variation shifts close to 180°. The curve maximizes in the second half of the day rather than the first. This suggests that the variation that Berthelier [1976] attributes to the McIntosh effect and the Kelvin-Helmholtz instability is in some way associated with reconnection

Conclusions

Ordering geomagnetic activity by the correct polarity of the IMF produces two annual waves whose amplitude is correctly predicted by the Russell-McPherron mechanism, as well as the observed amplitude and phase of the diurnal variation of geomagnetic activity. Berthelier [1976] neither separated polarities correctly nor used the proper amplitude of the effect of the southward field on geomagnetic activity. The phase of the summer-minus winter diurnal variation is significantly different than that expected for the McIntosh effect and this phase appears to depend on the polarity of the IMF. We are in the process of examining this dependence in more detail.

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