Possible dipole tilt dependence of dayside magnetopause reconnection

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[1] Recent studies suggest that the half-wave rectifier model of the interaction of the Earth's magnetosphere with the IMF is insufficient to produce the observed amplitude of the semi-annual variation. However, the observed amplitude would ensue if there is additional modulation of geomagnetic activity dependent on the tilt of the dipole axis. We use an MHD model to demonstrate that the size of the region of antiparallel magnetic field is controlled by the tilt of the Earth's dipole axis, and hence the integrated reconnection rate and geomagnetic activity may be so controlled. The same zero guide field model for the onset of reconnection also predicts that the maximum reconnection rate occurs not for due southward field but at angles away from due southward by about the dipole tilt angle. *INDEX TERMS:* 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 7835 Space Plasma Physics: Magnetic reconnection. **Citation:** Russell, C. T., Y. L. Wang, and J. Raeder, Possible dipole tilt dependence of dayside magnetopause reconnection, *Geophys. Res. Lett.*, *30*(18), 1937, doi:10.1029/2003GL017725, 2003.

1. Introduction

[2] Prior to 1973 there were three mechanisms proposed for the semiannual variation [*Cortie*, 1912; *Chapman and Bartels*, 1940]. The axial hypothesis held that the varying heliographic latitude of the Earth led to the variation. The equinoctial hypothesis attributed it to the tilt of the Earth's rotation axis. The third mechanism proposed that the flanks of the magnetopause were unstable to the Kelvin-Helmholtz instability [*Boller and Stolov*, 1970]. In 1973 *Russell and McPherron* [1973] noted that geomagnetic activity was controlled by the southward component of the interplanetary field as would be expected if merging or reconnection were occurring. Reconnection is a process which allows the flow of plasma between magnetic fields that have different topologies [*Vasyliunas*, 1975]. For example at the nose of the magnetosphere closed field lines, with two feet penetrating the Earth, come in contact with solar wind field lines that do not penetrate the Earth at all. If reconnection occurs then a new topological class of open field lines is created with one end in the Earth and the other in the solar wind. When a magnetic field line connected to the Earth also threads the flowing magnetosheath plasma it can (eventually) slow the solar wind flow and extract mechanical energy from the flow that is subsequently stored in the magnetotail.

[3] *Russell and McPherron* [1973] showed that if the merging took place via a half-wave rectification so that northward fields did not energize the magnetosphere, then a semiannual variation was produced statistically by the changing relative orientation of the magnetospheric magnetic field with the Parker-spiral, interplanetary magnetic field. Evidence for such a half-wave rectification has been presented for the AE index by *Arnoldy* [1971] and for the ring current by *Burton et al.* [1975]. A principal prediction of the model was that the semiannual variation could be separated into two annual variations according to the polarity of the IMF. This prediction was confirmed [*Russell and McPherron*, 1973]. This mechanism had both axial and equinoctial aspects and was consistent with the growing appreciation that reconnection was responsible for the coupling of the solar wind and the magnetosphere.

[4] The half-wave rectifier reconnection relationship found to be necessary by *Russell and McPherron* [1973] is incompatible with what has been called component merging since component merging [e.g., *Sonnerup*, 1974] predicts a gradual change in the merging rate as the IMF orientation changes from due south to due north. The alternate reconnection hypothesis, that exactly antiparallel magnetic fields are required for the onset of reconnection, produces reconnection sites that move away from the subsolar point when the IMF rotates away from due southward [*Crooker* 1979; *Luhmann et al.*, 1984]. Furthermore, the antiparallel merging law leads naturally to half-wave rectification because, as the IMF rotates northward, the reconnection point moves from the closed field lines of the low-latitude, dayside magnetosphere to open field lines of the polar cap. Since it is the process of the transfer of magnetic flux from the closed magnetosphere to the open lobes of the tail that is key to the energization of the magnetosphere, the motion of the reconnection point onto open field lines produces a sharp drop in the level of geomagnetic activity. Thus the Russell-McPherron hypothesis for the semiannual variation, the half-wave rectifier model of IMF control of geomagnetic activity, and antiparallel reconnection are mutually consistent hypotheses of magnetospheric behavior.

[5] Reconnection can occur both in a kinetic process and in a resistive situation such as found in a global MHD simulation of the magnetosphere where the resistivity may be supplied by the numerics. In a collisionless plasma this resistivity might be supplied by plasma waves. In either case exactly antiparallel magnetic fields might not be required, but they might still maximize the reconnection rate. The Earth's magnetopause may not behave like an MHD simulation predicts if there is not a source of resistivity, but reconnection could still occur in another way.

[6] Reconnection involves the breakdown of the frozen-in magnetic flux theorem to enable the scattering of particles

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from their original flux tubes. This need not be accomplished through collisions or wave-particle interactions. It could happen if the scale-size of the reconnection site was so small that the particles' adiabatic invariants were violated spatially. This has to happen to ions on at least the ion gyro scale and to electrons at the electron inertial length. An X-point geometry leads naturally to this condition as long as the magnetic field is very nearly antiparallel so that there is no significant component of the magnetic field along the neutral line. Such a field would guide the particles in the region of the X-point and could keep them tied to the magnetic field. Thus anti-parallel merging should be synonymous with zero-guide field collisionless reconnection. Evidence for such conditions at the reconnection point can be found in the study of magnetic reconnection at the high latitude magnetopause [*Scudder et al.*, 2002] where the magnetic field was seen to go to zero as the neutral point moved past the spacecraft. Supporting macroscale evidence for antiparallel reconnection has been drawn from the observed noon-time gap in auroral precipitation [*Coleman et al.*, 2001; *Petrinec and Fuselier*, 2003].

[7] Recently it has been noted that the simple merging law used by *Russell and McPherron* [1973] produces an amplitude for the semi-annual variation of geomagnetic activity that is smaller than observed [*Cliver et al.*, 2000]. *O'Brien and McPherron* [2002] have examined this question and concluded that a possible cause of the difference was a dependence of the reconnection rate on the tilt of the dipole axis to the solar wind. It is the purpose of this paper to demonstrate how it is possible that the tilt angle affects the reconnection rate. This modulation could occur by a variation in the length of the reconnection line. The problem at hand is to calculate realistically this length.

2. The Length of the Reconnection Line

[8] The two earlier attempts to calculate the length of the reconnection line defined by the point of anti-parallel fields were at most either qualitative or semi-quantitative. The first by *Crooker* [1979] used straight undeviated interplanetary fields against a dipole field. The second by *Luhmann et al.* [1984] used the convected-field, gas-dynamic model for the magnetosheath and an empirical model for the magnetospheric field. To try to improve upon this we use the UCLA-NOAA, MHD model of the global interaction [e.g., *Raeder et al.*, 2001] for both the magnetosheath and the magnetosphere to obtain a self-consistent solution for the two reconnecting fields. Since the MHD model enables reconnection through numerical resistivity and may develop reconnection not present in the real magnetosphere, we minimize reconnection by the simple device of running the code for northward IMF conditions and looking for the point of parallel fields rather than antiparallel fields. Reconnection does occur in the northward IMF case in the vicinity of the cusp but it has minimal effort in the subsolar region. Examination of the simulation results shows that the only noticeable subsolar influence of the cusp reconnection is to supply plasma to the dayside magnetosphere just inside the boundary. We make runs at a variety of "southward fields", corresponding to clock angles of 180° (due south), 165°, 150°, and 135°, at zero degree tilt angle (solar wind flow perpendicular to the dipole axis). We then repeat the simulations for tilt angles of 15° and 30°, angles representative of the annual variation of dipole tilt, up to 34°.

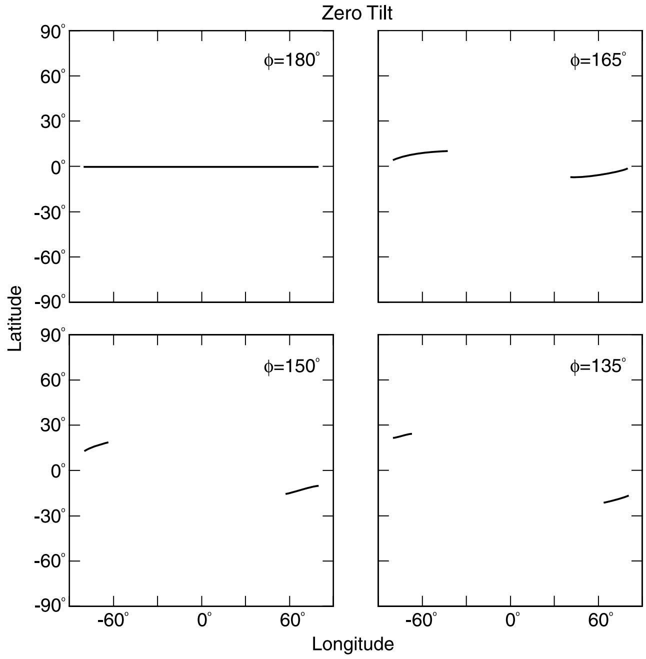

Figure 1. Solid line shows region of antiparallel fields in the magnetosheath and magnetosphere for a dipole tilt of zero degrees and IMF clock angles of 180°, 165°, 150° and 135° as inferred from a global MHD simulation.

3. The Simulation Results

[9] Figure 1 shows the region of anti-parallel magnetic field for 0° tilt and clock angles of 180°, 165°, 150°, and 135°. The field lines used are the first open and first closed on either side of the magnetopause. Because of the finite thickness of the magnetopause in the simulation grid we accept fields of up to 178° apart as being antiparallel. As expected from previous studies, the reconnection line is straight across the magnetopause for due southward IMF. The reconnection line splits for fields that are not due southward and moves northward and southward on either side of noon (depending on the direction of By). We have chosen By negative (dusk to dawn) here. Figure 2 shows the same plot but for 15° tilt angle. The most dramatic change is for due southward IMF where the neutral line has shrunk tremendously. Otherwise the neutral lines are qualitatively similar to that for 0° tilt but everywhere shorter. We note that 'reconnection' line segments have become horizontal in the tilted dipole case. This is in part a real effect but is also in part due to the finite grid size of the simulation that does not resolve slight tilts of these lines. Figure 3 shows the case of 30° tilt. The neutral line again shrinks everywhere. We note that the maximum length has moved away from due south orientations to intermediate shear angles.

[10] Figure 4 summarizes the behavior of the length of the neutral line as a function of tilt and clock angle. There is a dramatic change in the length of the neutral line for due south fields as the tilt angle changes. The change is only slightly less dramatic at 165°. At more horizontal orientations the behavior is qualitatively similar but smaller. As a

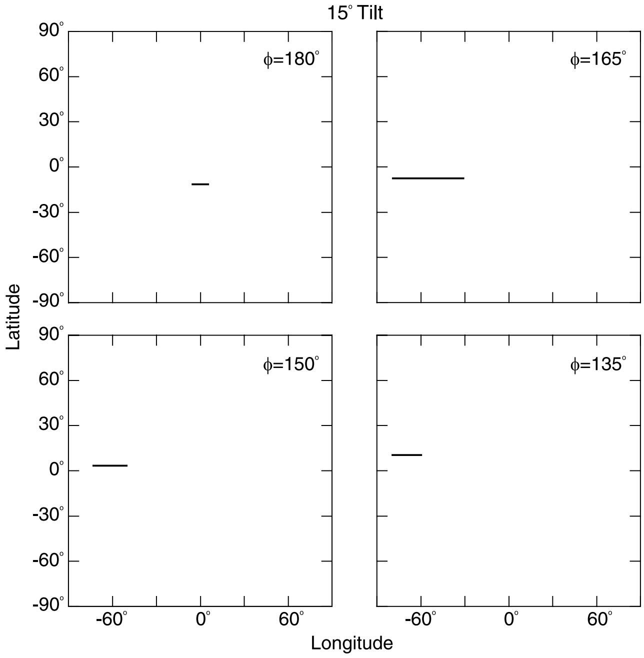

Figure 2. Solid line shows region of antiparallel fields for a dipole tilt of 15° and IMF clock angles of 180°, 165°, 150° and 135°.

result of these changes, as we noted above, the length of the neutral line maximizes at clock angles that may be well away from due south.

4. Discussion

[11] These results provide insight into how dipole tilt might affect geomagnetic activity. However, they should not be construed to be the last word on this subject. They should be treated more as guidance. The reconnection rate itself should be proportional to more than just the length of the neutral line. The plasma conditions and in particular the Alfven velocity should also matter as might the local curvature of the magnetopause. Furthermore, the reconnection process may distort the magnetosheath flow and geometry of the magnetosphere, altering the length of the neutral line. Our approach, attempting to find undistorted antiparallel points on the magnetopause, is akin to searching for regions in which kinetic processes might initiate reconnection in the absence of other sources of resistivity. In any event the problem is very non-linear. Nevertheless, we believe that our approach is qualitatively correct. Tilting the dipole does affect reconnection.

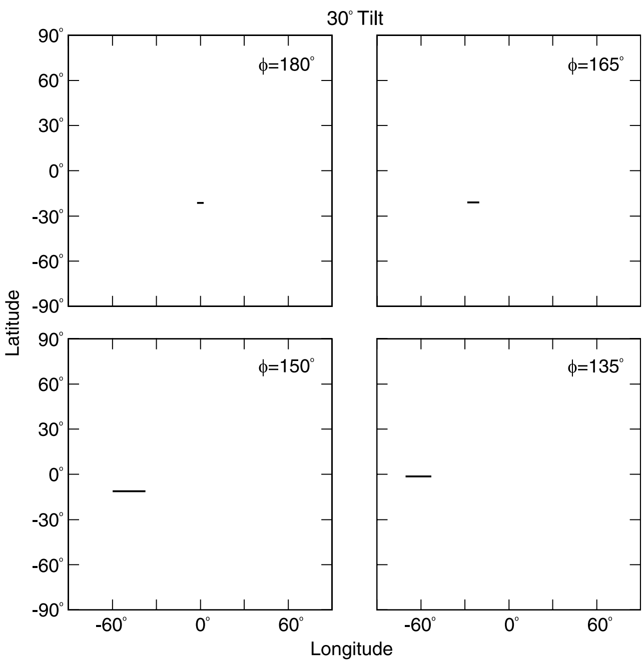

Figure 3. Solid line shows region of antiparallel fields for a dipole tilt of 30° and IMF clock angles of 180°, 165°, 150° and 135°.

[12] In order to determine the joint effect of tilt and clock angle on reconnection, it is perhaps best to adopt an empirical approach and use geomagnetic activity as a proxy for reconnection. *O'Brien and McPherron* [2002] have made an initial attempt at this but our results suggest they need to include the clock angle in their study as well. It is perhaps worth noting that although the idealized treatment here predicts very large tilt and clock effects, this may be difficult to detect because tilt and IMF clock angle are constantly changing unless a study is specifically designed to detect these dependencies.

[13] The implication for the semiannual variation is also clear. Our ideas about the physics of reconnection need not be changed. Antiparallel reconnection may very well be

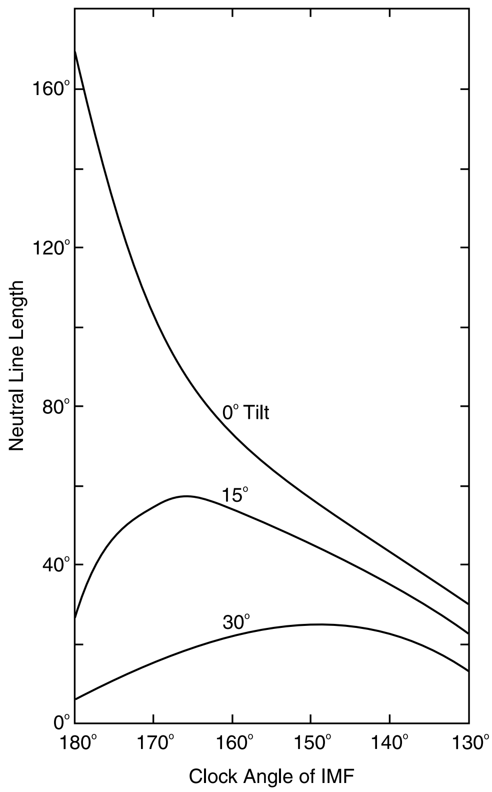

Figure 4. Length of the neutral line versus IMF clock angle for the tilt angles of 0°, 15° and 30°. Smooth line has been drawn through the values deduced from the lengths displayed in Figures 1–3.

operative as expected from theoretical considerations. The geometry of the neutral line adds an additional factor in controlling the reconnection rate and the consequent geomagnetic activity. The basic cause of the semiannual variation of geomagnetic activity may be just as proposed by *Russell and McPherron* [1973]. We simply need to add the empirical tilt angle affect to the reconnection rate.

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