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PROXY AND IN-SITU STUDIES OF DAYSIDE MAGNETOPAUSE RECONNECTION

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ABSTRACT

The functional dependence of magnetic reconnection on solar wind parameters is examined utilizing the *am* geomagnetic index and satellite observations at the magnetopause. Several parameters in the solar wind are found to control geomagnetic activity. Reconnection is found to be most efficient when the interplanetary magnetic field is southward, although some activity remains when the IMF is horizontal and slightly northward. The reconnection efficiency increases with the solar wind dynamic pressure but decreases when the Mach number is greater than 7.5. These results are compared with the functional dependencies found by correlating solar wind and magnetosheath measurements with observations of accelerated flows at the magnetopause. Accelerated flows are found to occur most often when the interplanetary magnetic field is directed southward. However, accelerated flows do occur when the IMF is horizontal and northward. Accelerated flows are also affected by the magnetosheath beta such that higher beta inhibits their occurrence. The location of accelerated flows indicates that reconnection occurs mainly at the subsolar point.

1. INTRODUCTION

Reconnection at the dayside magnetopause controls the transfer of magnetic flux and energy into the magnetotail. The subsequent release of this energy into the nightside magnetosphere and ultimately the ionosphere and atmosphere produces geomagnetic activity, which is most often characterized by its effects in ground based magnetic records. This release of energy can have significant societal consequences. Large magnetic perturbations can have harmful effects on power distribution grids. Energetic particles can damage satellite systems, and disturbances in the ionosphere can disrupt communications. The ability to predict this activity could allow measures to be taken to protect these systems. One method of predicting this activity is to use the knowledge of its functional dependence on solar wind parameters combined with in situ measurements of the solar wind and the interplanetary magnetic field. Many studies have correlated upstream parameters with various geomagnetic activity indices. Early correlation studies provided a basis for anticipating what parameters control geomagnetic activity. Perhaps one of the most unambiguous correlations was that of activity with increasing southward field magnitude [*Fairfield and Cahill*, 1966, *Rostoker and Fälthammar*, 1967]. This correlation is expected for the reconnection model of *Dungey* [1961]. Interplanetary magnetic field lines merge with magnetospheric field lines on the dayside and then convect over the polar cap to the tail. The

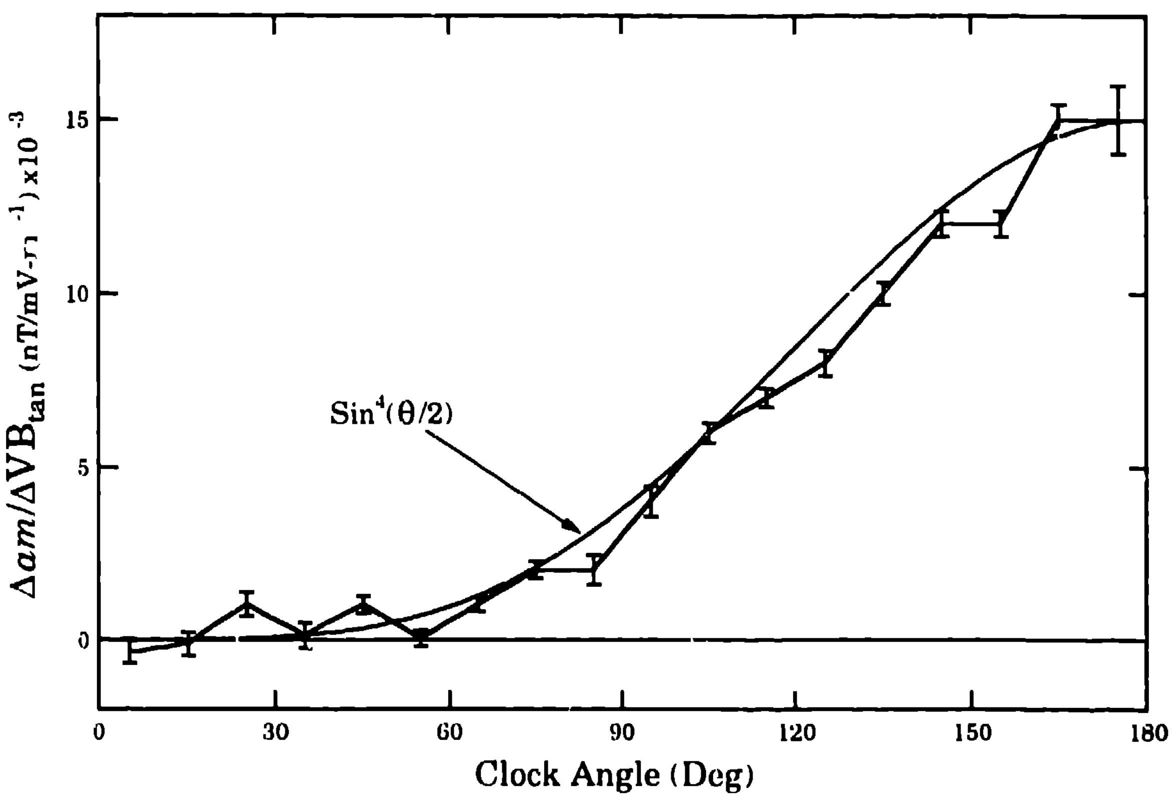

Fig. 1. The "reconnection efficiency" as measured by the *am* index with increasing IMF clock angle (*Scurry and Russell*, 1991).

increased magnetic flux in the tail produced by this process is returned to the dayside after it reconnects in the center of the tail. The energy released drives auroral currents and other manifestations of substorm activity. *Arnoldy* [1971] found the magnetosphere to act as a half-wave rectifier in which only the southward component of the IMF contributed to increased geomagnetic activity as measured by the auroral electrojet or AE index. *Perreault and Akasofu* [1978] found activity is also produced when the interplanetary field is horizontal (east-west). Studies of the *am* index have indicated that while effects due to viscous interactions with the solar wind flow and dynamic pressure fluctuations are detectable, reconnection is the dominant mechanism providing the energy for geomagnetic activity [*Scurry and Russell*, 1991]. Many forms have been proposed for the functional dependence between solar wind variables and geomagnetic activity, also termed the coupling function. *Vasyliunas et al.* [1982] attempted to limit the number of possible scaling relations by determining a family of coupling functions with the proper units. Most of these coupling functions are similar in that they predict an increase of activity with increasing southward field, or more precisely the amount of southward magnetic flux carried to the magnetopause per unit time. This effect is so dominant that other terms have little contribution to the overall correlation between predicted and measured activity [*Gonzalez et al.*, 1989]. Our objective is to determine the form of the coupling function through proxy studies of geomagnetic indices and then to learn more about what controls the reconnection process.

This study compares the results of a study of dayside reconnection using the *am* index as a proxy measure of the rate of dayside reconnection and using direct observations of dayside reconnection using the ISEE 2 data. The correlation study with the *am* index reveals some important functional dependencies

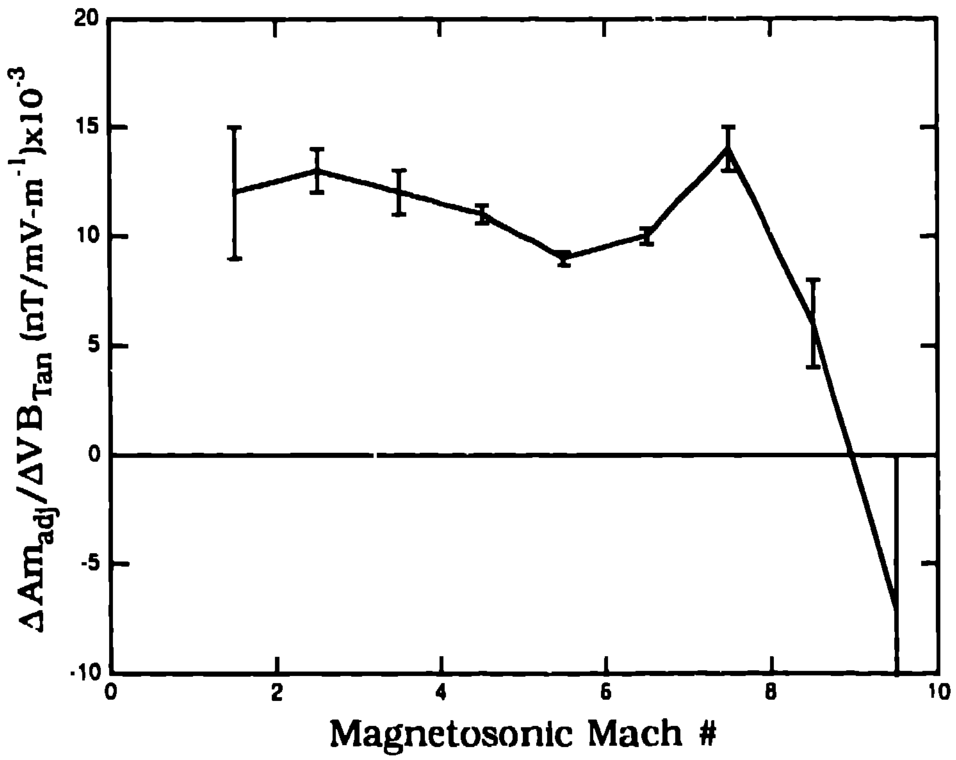

Fig. 2. The "reconnection efficiency" for increasing solar wind magnetosonic Mach number (*Scurry and Russell*, 1991).

of reconnection on upstream parameters. The effects of these controlling parameters on reconnection, as observed at the magnetopause, should be evident as well. The goal is to understand the dependence of the rate and occurrence of dayside reconnection on solar wind conditions.

2. THE DATA BASE

The data base utilized in the correlation study was derived using one-hour solar wind magnetic field and plasma data from the OMNI database at NSSDC. The data were then separated by IMF polarity and averaged over three hours to match the three-hour *am* index. Since the IMF can fluctuate in direction during any one hour interval it is possible for there to be significant periods of southward IMF within the one hour interval when the average over the interval is northward and vice versa. In order to reduce this effect we required that all three 1-hour averages be northward(southward) for any 3-hour northward(southward) interval. The *am* index was chosen since it has good global coverage and it is constructed such that it has little bias due to the distribution of stations.

A data base of magnetopause crossings was created using magnetic field and plasma data from the ISEE 2 spacecraft. Reconnection events are identified using three criteria. The first criterion is the existence of an acceleration of plasma earthward or inside the magnetopause current layer. This acceleration can be an increase in the plasma flow speed or simply a change in the flow direction. The second criterion is that this accelerated flow should consist of magnetosheath like plasma as distinguished by the plasma density and temperature. The last criterion is that these events should roughly satisfy tangential stress balance. Although the dataset contains a large number of accelerated flow events, it is by no means all the events in the ISEE dataset. Measurements of the local magnetic shear across the

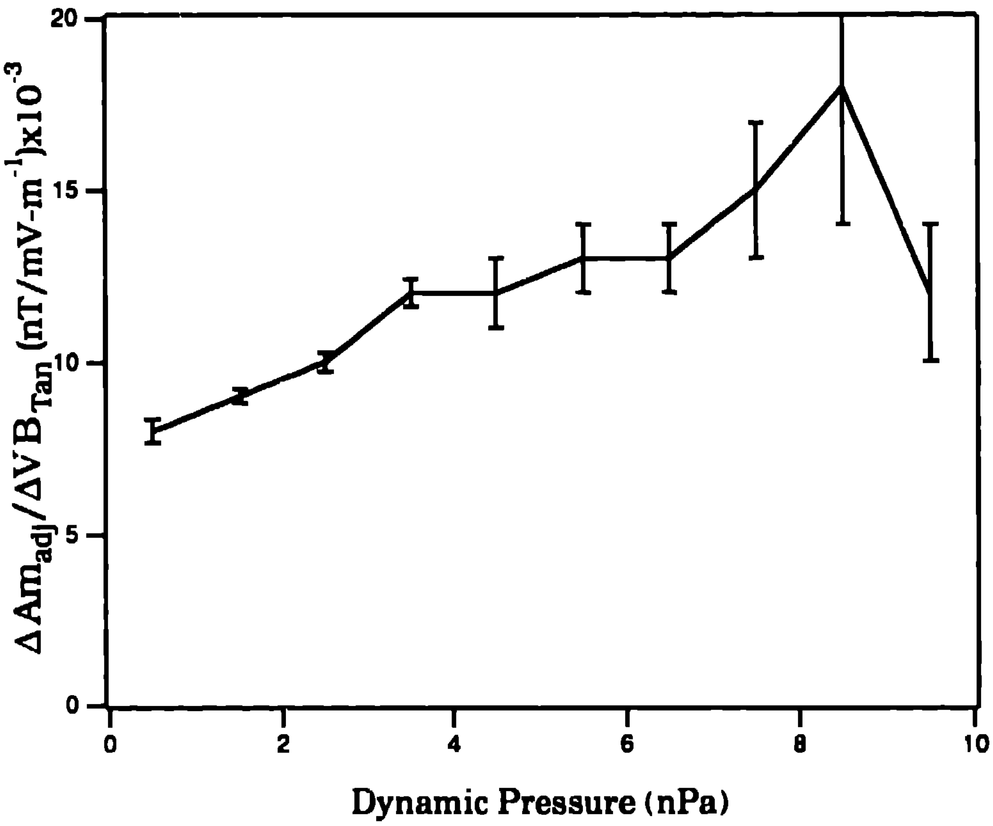

Fig. 3. The "reconnection efficiency" for increasing solar wind dynamic pressure (*Scurry and Russell*, 1991).

magnetopause and magnetosheath plasma parameters are taken for each magnetopause crossing.

3. GEOMAGNETIC ACTIVITY

Correlation studies of geomagnetic indices with the solar wind have previously been used to determine how the solar wind controls activity. In such studies the geomagnetic index serves as a proxy measure of the physical process we desire to measure but cannot. This paper focuses on the results of a correlation study using the *am* geomagnetic index to examine the functional form of reconnection. In order to use this index as a proxy for the reconnection process, effects from viscous interactions and dynamic pressure fluctuations must be removed. The effects from non-reconnection phenomena are identified by determining their functional form during times of northward IMF as described by *Scurry and Russell* [1991]. A measure of the "reconnection efficiency" is found by examining the increase in the *am* index in relation to the increase in incoming flux (the solar wind velocity multiplied by the field magnitude tangential to the magnetopause). When this is done the functional dependence of the *am* index on the clock angle of the IMF is found to resemble the $\sin^4(\theta/2)$ function put forth by *Perreault and Akasofu* [1978] and often used by others [*Gonzalez et al.*, 1990]. As shown in Figure 1, this function suggests that reconnection at the magnetopause is most efficient when the IMF is directed southward opposite to the Earth's dipole field. When the IMF is horizontal (perpendicular to the dipole axis) a non-zero reconnection efficiency is inferred. This suggests that either a large magnetic shear at the subsolar point is unnecessary for reconnection, that reconnection occurs at other locations at the magnetopause where the shear is larger, or that during periods of average horizontal fields occasional southward fields arise

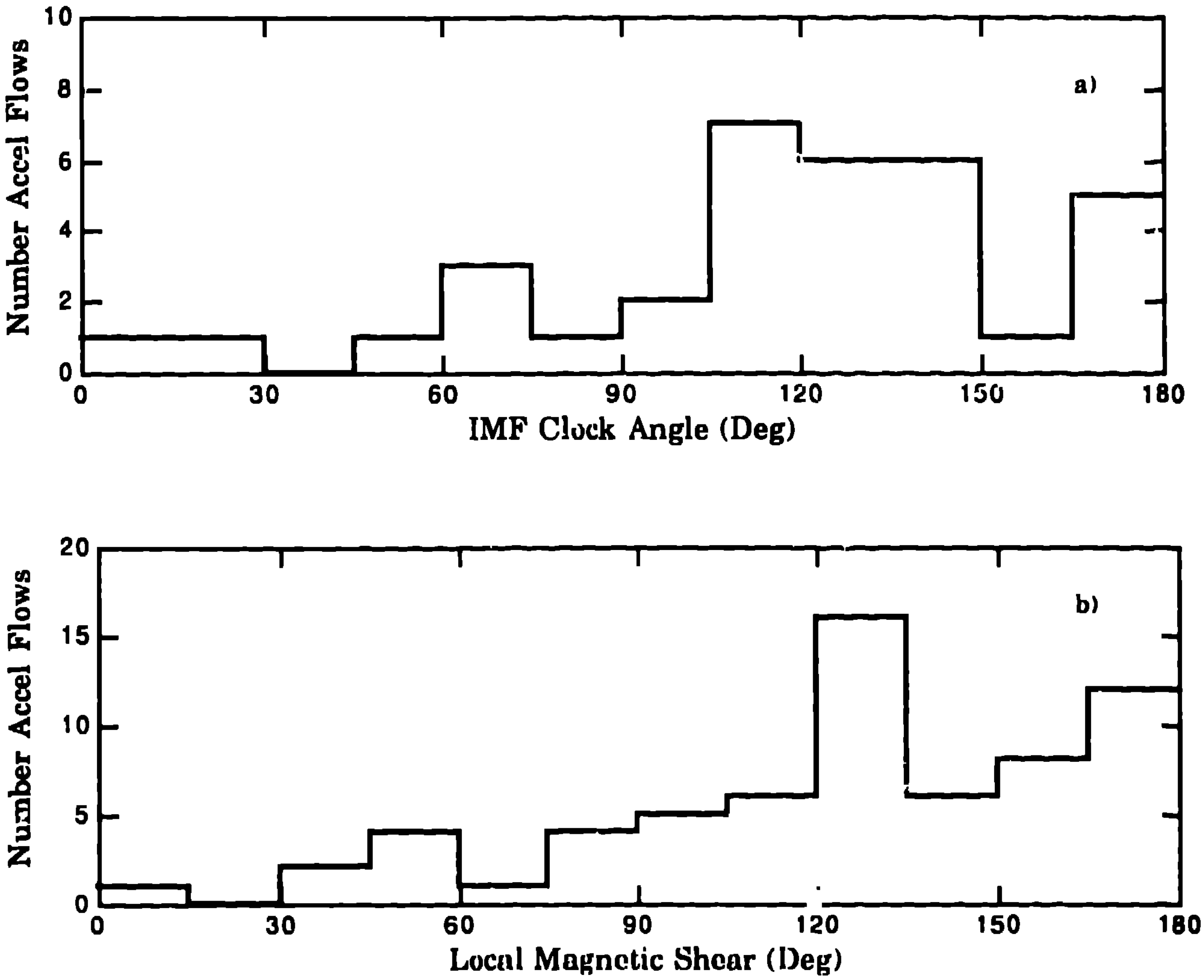

Fig. 4. The observed number of accelerated flows for 15° bins of a) upstream IMF clock angle, b) local magnetic shear.

and cause activity. Our correlation study cannot distinguish between these possibilities.

Since reconnection is dependent on the local plasma environment as well as the magnetic shear, changes in the upstream solar wind plasma conditions could affect the "reconnection efficiency". The magnetosonic Mach number is found to have a significant effect at high Mach number. As shown in Figure 2 the "reconnection efficiency" is found to remain constant with increasing Mach number until about M_{MS}=7.5 where it decreases substantially. This effect may result from changes in the magnetosheath beta with increasing Mach number.

The solar wind dynamic pressure squeezes the magnetosheath field lines against the magnetopause boundary. An increase of the pressure between the field lines in the sheath and the magnetosphere should therefore enhance their merging rate. The dependence of reconnection efficiency on dynamic pressure, shown in Figure 3 is consistent with this expectation.

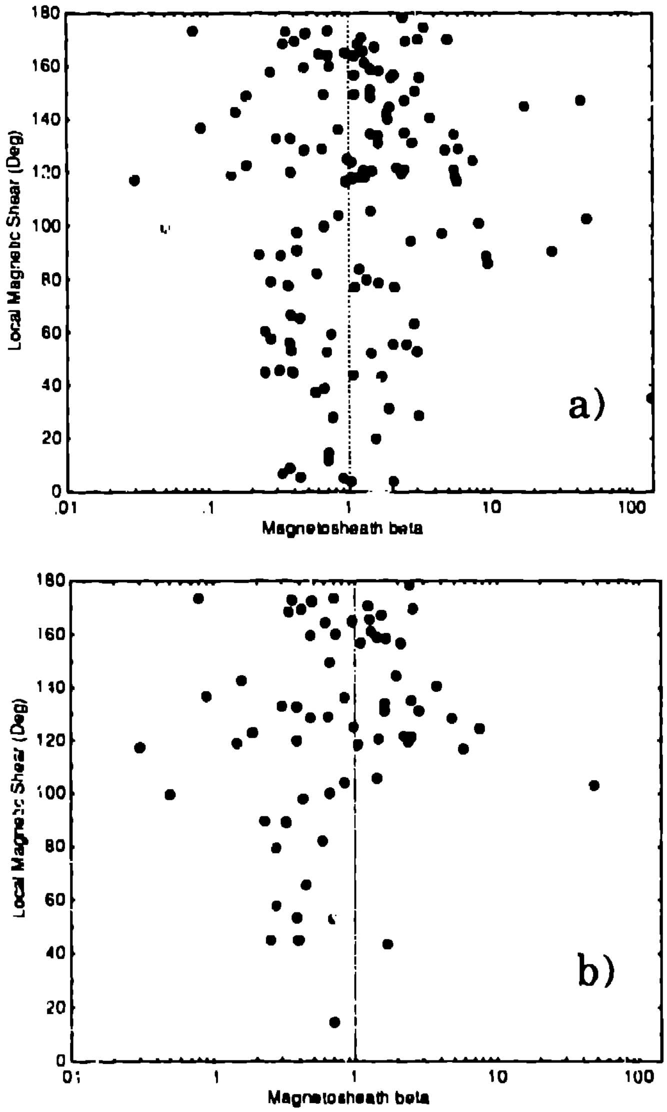

Fig. 5. Magnetosheath beta and local magnetic shear for a) all magnetopause crossings and b) accelerated flow events.

4. MAGNETOPAUSE OBSERVATIONS

A more direct method of determining the functional dependence of reconnection at the magnetopause on various solar wind and sheath parameters is to correlate these parameters with satellite observations of the behavior of the magnetic field and plasma at and near the magnetopause. Reconnection at the magnetopause is characterized by the existence of a magnetic field component normal to the boundary and by the acceleration of plasma as it passes across the boundary. Furthermore the magnetopause is expected to take the form of a rotational discontinuity during reconnection [*Levy et al.*, 1973]. These signatures are expected to be detectable away from the actual merging site. Thus the observation of an accelerated flow simply implies that reconnection has taken place somewhere on the magnetopause on the field lines being sampled but not necessarily at the location of the spacecraft. For example, reconnection could take place at high latitudes and accelerate plasma toward the equatorial plane. Figure

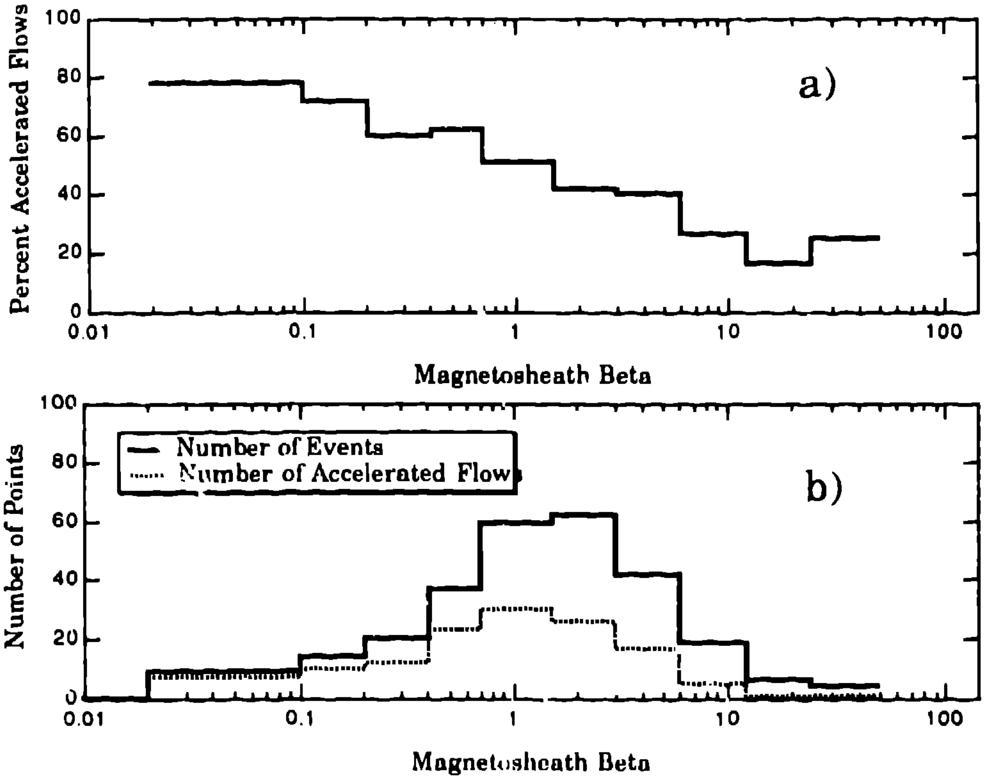

Fig. 6. a) The occurrence rate of accelerated flows for increasing magnetosheath beta b) The distribution of events with beta.

4 shows the dependence of the occurrence of accelerated flows as observed by ISEE 2 on both the upstream solar wind IMF direction and the local magnetic shear across the magnetopause. The occurrence rate of accelerated flows is the ratio of magnetopause crossings with the accelerated flow signature to the total number of magnetopause crossings in that parameter bin. The IMF clock angle is measured using observations in the upstream solar wind (ISEE 3 and IMP 8). The local magnetic shear is the angle between the field vectors across the magnetopause boundary. The functional dependence of the occurrence of accelerated flows is different from that found using the *am* index. The greatest occurrence of accelerated flows is still for southward fields, but a non-zero occurrence of accelerated flows is found for northward IMF conditions as well. These two apparently contradictory results may arise from differences in the site of reconnection for northward and southward IMF. Northward IMF field

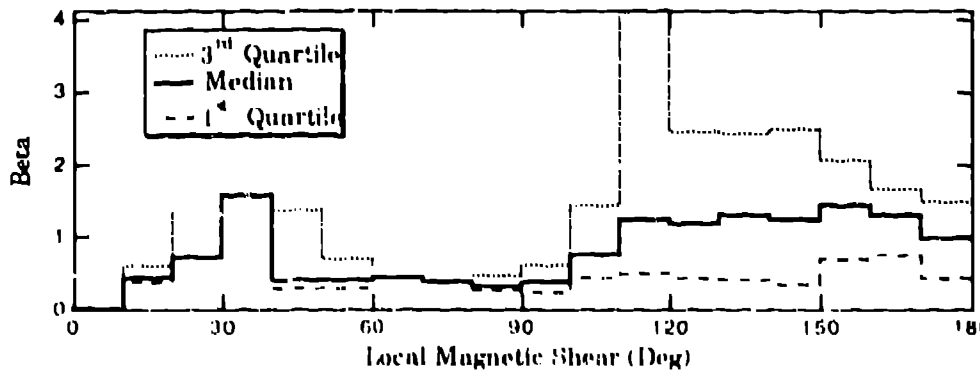

Fig. 7. The distribution of magnetosheath beta as measured for accelerated flow events in 10° bins of local magnetic shear across the magnetopause.

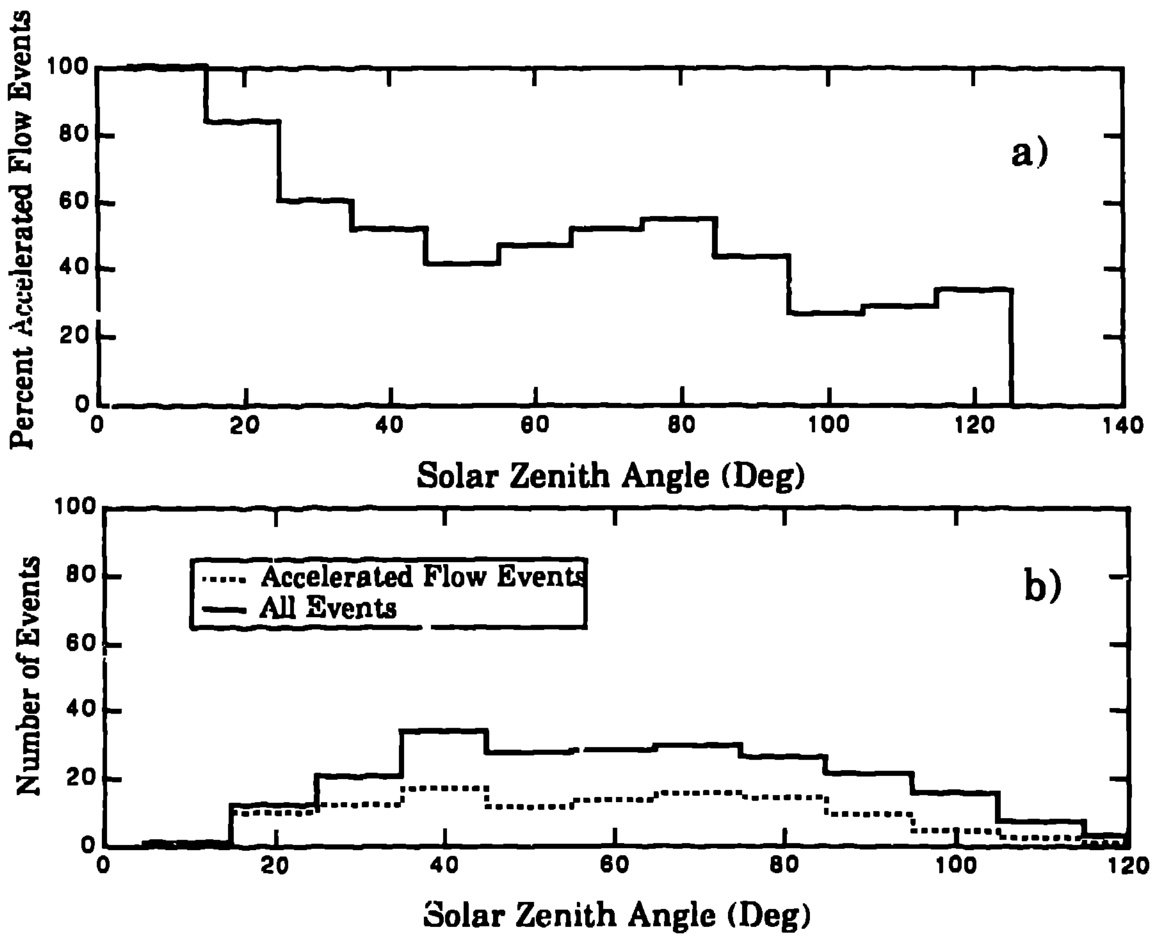

Fig. 8. a) The occurrence rate of accelerated flows for increasing solar zenith angle as measure away from the subsolar point. b) The distribution of events over solar zenith angle.

lines may merge with magnetospheric field lines that are already open. Such reconnection does not increase the flux in the tail, and does not thereby energize the magnetosphere as does reconnection of southward fields, but may still produce accelerated flows. The *am* index is not expected to be sensitive to convection produced by merging on the high latitude magnetopause.

The accelerated flow signature may be observed some distance away from the actual site of reconnection. Therefore, the shear measured at the observation site may differ from that at the point of merging. Although low shear events are observed near the subsolar region, they may be the result of merging occurring at much higher latitudes. Perhaps the *am* index's lack of sensitivity to high latitude reconnection, is the reason for the dissimilarity between the *am* index and the accelerated flow dependence on the IMF. Nevertheless, the functional dependence of accelerated flows on local magnetic shear implies that a large shear is not necessary for reconnection to occur (see also *Gosling et al.* [1990]). These results are inconsistent with anti-parallel merging models which expect reconnection to occur only where the fields are locally anti-parallel. Anti-parallel merging models are based on the idea that the field shear at the point of merging is the dominant factor determining if merging initiates. For example, the growth rates of certain current instabilities, such as the tearing mode, are greatest when the field shear is large. These instabilities are though to be a precursor to merging. The fact that merging occurs for a wide range of field shear may indicate that other factors such as the plasma beta or relative flow speed

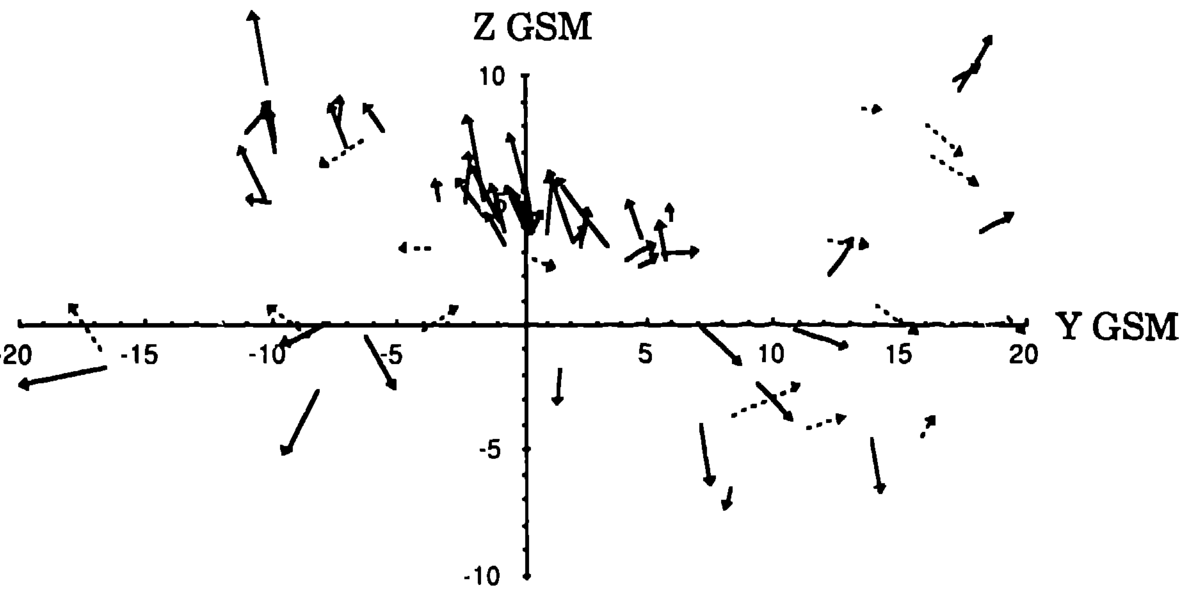

Fig. 9. The location and direction of all accelerated flow events. Dashed vectors show a reversal in V_z across magnetopause.

across the boundary may affect the initiation of merging.

One of the plasma parameters in the sheath that is expected to affect reconnection is beta, the ratio of the plasma thermal pressure to magnetic pressure. Its effect on accelerated flows has been observed by *Paschmann et al.* [1986]. *Gosling et al.* [1990], however, observed no dependence of the ratio of measured to predicted velocity change across the magnetopause on beta in their study of plasma flow reversals. Magnetopause crossing events and those with accelerated flows are plotted in relation to local magnetic shear and ion beta in Figure 5. The plasma beta is measured in the sheath outside the magnetopause. It can be seen that accelerated flows occur over a wide range of beta as well as shear. In Figure 6 we examine the occurrence rate of accelerated flows with increasing plasma beta. As the beta increases the occurrence rate of accelerated flows decreases. Despite this dependence, most accelerated flow events occur for moderate beta conditions since the peak of the distribution as a function of beta is centered around $\beta = 2$. Figure 7 examines the relationship between beta and local magnetic shear when accelerated flows are observed. Accelerated flows observed when the shear is small generally occur during low magnetosheath beta. The large shear events are not as restricted in beta. This implies that a low magnetosheath beta is necessary for low shear reconnection.

The occurrence of accelerated flows as a function of solar zenith angle is plotted in Figure 8. The occurrence rate is greatest near the subsolar point. This may be due to the larger dynamic pressure and stagnation of plasma near the nose. A direct examination of the affect of dynamic pressure on reconnection has not been done due to the lack of sufficient upstream plasma data. However, in the future we may use an inferred upstream pressure derived from the magnetopause location and field magnitude. The higher occurrence rate of accelerated flows near the magnetopause nose agree with the subsolar merging paradigm. Merging initiates at the subsolar point where the interplanetary field reaches the magnetopause first and the pressure and the flow stagnation is greatest. These results also disagree with anti-parallel merging models which expect merging to occur at the subsolar point only when the IMF is directed due south [*Crooker*, 1979].

Reconnection has been previously found to occur not only near the subsolar point but also far away from the subsolar point both at high latitudes [*Gosling et al.*, 1991] and at lower latitudes along the tail flanks [*Gosling et al.*, 1986]. The high-latitude reconnection events take place on open magnetospheric field lines. These events are of large local magnetic shear. Thus, away from the subsolar point, where the flow is no longer stagnated and the pressure against the boundary is less, a large field shear becomes a more important factor for the occurrence of reconnection. Figure 9 shows the location and flow direction of the accelerated flow events in the y-z GSM plane. Although most of the vectors radiate away from the subsolar point and the equator, several of these events are indicative of reconnection occurring away from the equator. These events are characterized by a reversal of the flow in the z-GSM direction as the spacecraft traverses the magnetopause. According to previous results we expect these events to be of large shear or low beta since they occur away from the more ideal conditions of the subsolar point. If merging usually occurs over some finite length in the equatorial region, then the accelerated flows which occur away from the equator may indicate that the merging line tilts (*Sonnerup*, 1974). This X-line tilt may be in response to changes in the IMF direction.

5. CONCLUSIONS

This examination of the functional dependence of the *am* index and dayside reconnection has revealed important results useful in predicting geomagnetic activity. Accelerated flows are found to occur over a wide range of upstream IMF clock angles and local magnetic shear. Accelerated flows observed with low shear occur only when the magnetosheath beta is low. A high magnetosheath beta decreases the occurrence rate of accelerated flows The subsolar point is the usual location for reconnection. However reconnection can occur away from the subsolar equator when the local shear is high and the magnetosheath beta is sufficiently low.

6. ACKNOWLEDGMENTS

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