THE EFFECT OF SOLAR WIND DYNAMIC PRESSURE ON THE EARTH'S MAGNETOSPHERE

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ABSTRACT

The dynamic pressure that the solar wind exerts on the Earth's magnetosphere is equal to the momentum flux of the solar wind decreased by about 11% due to the divergence of the streamlines of the magnetosheath around the magnetosphere. This solar wind pressure confines the Earth's magnetic field to a cavity in which the field is more than doubled at the nose. The size of this cavity depends on the inverse sixth root of the dynamic pressure. The magnetopause moves inward from this equilibrium position when the IMF is southward and moves outward when the ring current becomes energized. On the surface of the Earth the magnetic field is compressed in proportion to the change of the square root of the dynamic pressure. Low latitude stations such as Wake also respond to changes of the equatorial electrojet. Subauroral stations such as Tucson, Tampa Bay and Boulder respond also to changes in the auroral currents. Thus the latitudes most responsive to solar wind conditions are from about 15° to 30° (Tahiti to San Juan). Stations of the IGS chain allow us to probe the rate of change of the field at those latitudes of most interest to power distribution systems.

1. INTRODUCTION

The study of the solar wind interaction with the magnetosphere is one of the oldest investigations of the magnetosphere. It began, perhaps, with Chapman and Ferraro's [1931] model for the geomagnetic storm. In this model a transient stream of solar plasma confines the magnetic field of the Earth to a cavity, which we now call the magnetosphere. The earliest model of this magnetosphere, treated the solar plasma as if it were bounded by a flat plane whose normal was in the direction of the plasma flow. In this approximation it can be readily shown that the magnetic field lines of the Earth's dipole deform as if there were a second or mirror dipole equidistant from the advancing front on the far side of the front and of equal magnitude to that of the Earth. It is easy to show that the magnetic field just inside the advancing front, or magnetopause as we now call it, is doubled.

This model is very idealized because in the real interaction the solar plasma, or solar wind as it is now known, completely envelops the terrestrial magnetosphere. Moreover, now we know that the solar wind flows continuously. The sudden increases in the magnetic field on the surface of the Earth, often associated with magnetic storms, are caused by sudden increases in dynamic pressure associated with the passage of shocks in the solar wind. These shocks are collisionless in the usual sense of the word, but not dissipationless, nevertheless.

The modern equivalent of the image dipole model of the Earth's magnetosphere is shown in Figure 1. This magnetosphere has been constructed analytically by placing a magnetic dipole in a vacuum enclosed by a elliptical superconductor with circular cross section [Tsyganenko, 1989a]. This model is very much akin to the original image dipole model because the only

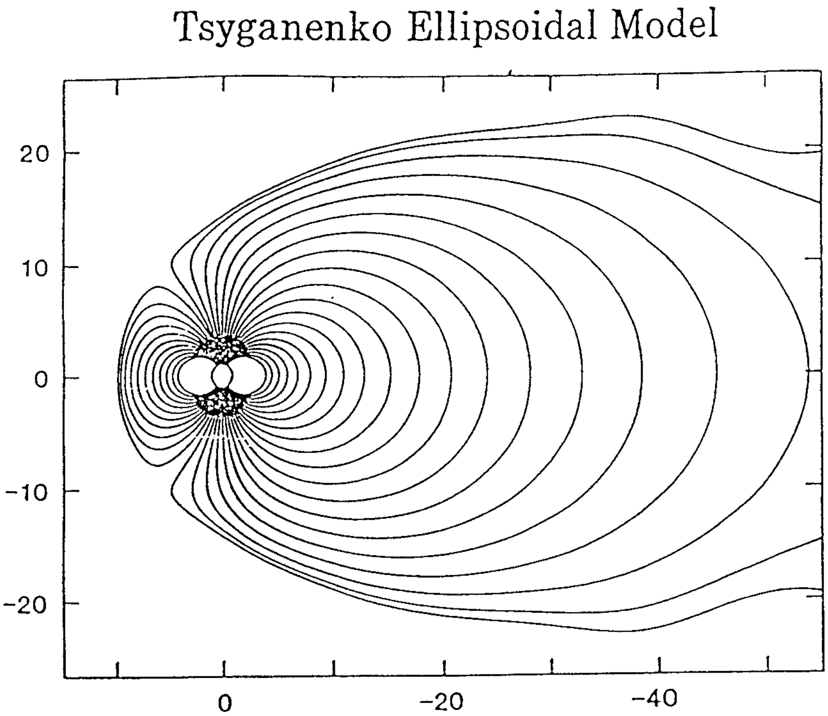

Fig. 1. Vacuum model of magnetosphere [Tsyganenko, 1989a]. In this model a magnetic dipole is placed within a superconducting ellipsoid of revolution whose shape approximates that of the terrestrial magnetopause.

plasma considered is that outside the magnetosphere proper. Further, like the image dipole model, the model can be scaled to any solar wind dynamic pressure. Empirical models of the magnetosphere, such as Tsyganenko's [1989b] more famous model, cannot be compressed.

In order to understand how much to compress the magnetopause due to solar wind dynamic pressure increases we must understand both how hard the solar wind pushes on the magnetosphere and how strong is the magnetic pressure in the compressed magnetosphere. The correct answer was not immediately obvious to early magnetospheric researchers as the new measurements of the space age forced them to attempt to construct realistic models of the magnetosphere.

The first question that had to be answered was whether the solar wind was reflected from the magnetic field of the Earth elastically so that it imparted a normal stress equal to twice the product of its mass flux and velocity or whether it interacted inelastically. While it is obvious to observers in the 1990's that the solar wind does not bounce off the Earth's magnetosphere and return to the Sun but is rather deflected around the obstacle, there were many who considered the interaction to be elastic [Spitzer, 1956; Dungey, 1958; Zhigulev and Romishevski, 1960; Beard, 1960, Mead and Beard, 1964; Mead, 1964; Siscoe et al., 1968]. Others adopted the modern understanding [Chapman, 1960; Ferraro, 1960; Obayashi and Hakura, 1960; Piddington, 1960; Dungey, 1961; Parker, 1961]. A secondary effect, the divergence of streamlines around

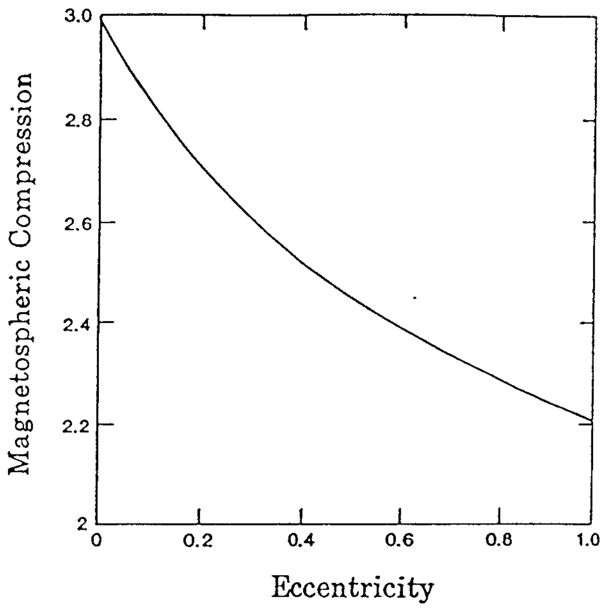

Fig. 2. Compression of the magnetic field just inside the nose of the magnetosphere as a function of the shape of the magnetopause as measured by the eccentricity of the ellipsoid of revolution that confines the magnetic field. A spherical magnetopause has an eccentricity of zero and a paraboloid of revolution an eccentricity of unity.

the magnetosphere, further reduces the pressure by about 11% [Spreiter et al., 1966].

Another incorrect paradigm adopted by most early researchers has had a very stubborn persistence and still exists in some quarters today. This is the assumption that is correct for the image dipole, but not for the model of Figure 1, that the magnetic field is doubled just inside the boundary. In fact, in realistically shaped magnetospheres the magnetic field is much more than doubled. The factor is about 2.44. The erroneous doubling assumption was used by Beard [1960] in his attempt to determine the shape of the magnetosphere, by Ferraro [1960] in his 2-D magnetospheric model, and by Spreiter and Briggs [1962] in their 3-D model.

Since we are going to make much use of the Tsyganenko [1989a] model shown in Figure 1, we should say a few words about its advantages over other apparently similar vacuum models. Mead [1964] constructed perhaps the first such model. However, since it used spherical harmonic coefficients, it became inaccurate when a distance of 10 Earth radii (R_E) was reached on both the day and night sides of the Earth. This model had no capability to tilt the dipole but this feature was later added by Choe et al. [1973]. A more realistic approach, placing the dipole in a paraboloid of revolution was first suggested by Alekseev and Shabansky [1972] and implemented with Bessel functions by Stern [1985]. This model provided a reasonable dayside field but the nightside magnetic field expanded too rapidly. The Tsyganenko [1989a] ellipsoid of revolution cures this problem. It is our present best vacuum model of the magnetosphere.

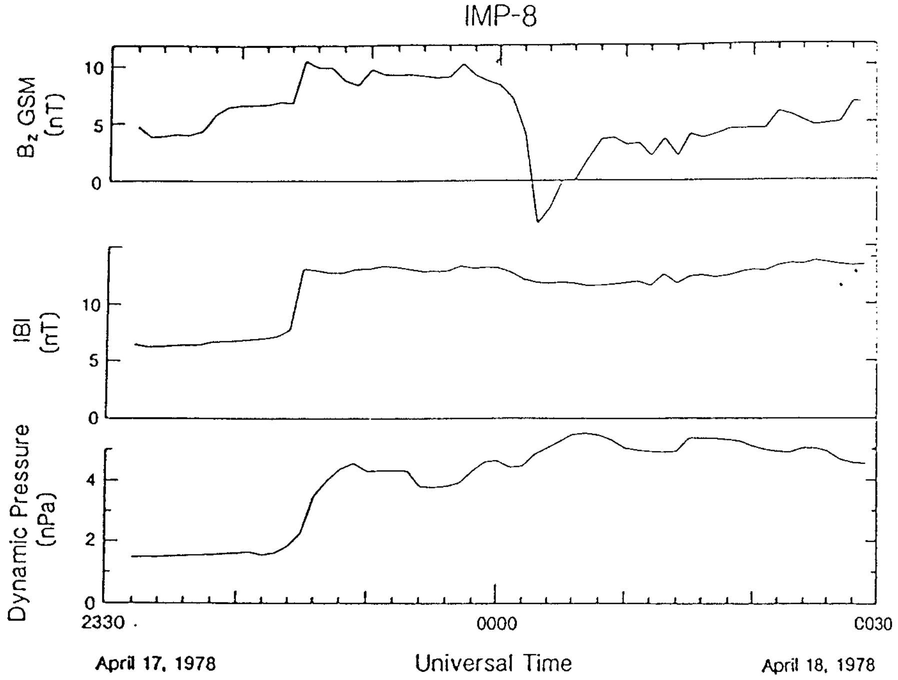

Fig. 3. the increase in dynamic pressure (bottom) magnetic field strength, (middle) and north-south field in magnetospheric coordinates during the passage of an interplanetary shock as measured by IMP-8 on April 17, 1978.

The shape of the ellipsoid is variable as is the actual shape of the magnetosphere. It should be noted that the terrestrial magnetopause shape is not an ellipsoid of revolution. We can vary the ellipticity of the model to illustrate the variability of the compression of the field at the nose of the magnetosphere. Figure 2 illustrates this. For an ellipticity of 0 the magnetosphere is a sphere and the field as tripled at the nose and, in fact, all around the equator. If the ellipticity is 1 then the magnetopause is a paraboloid of revolution and the field increase is 2.2. If the model allowed an infinite ellipticity, the magnetopause would be a plane and the field at the nose would merely be doubled by the compression.

2. SURFACE RESPONSE AT LOW LATITUDE

Interplanetary shocks can be driven by coronal mass ejections from the sun, by the interaction of fast and slow streams, and possibly by other processes as well. As illustrated in Figure 3, an interplanetary shock causes an increase in the number density of the plasma, the velocity, the plasma temperature and the magnetic field strength. (Occasionally reverse shocks can be formed which propagate toward the sun but more slowly than the outward solar wind flow. These reverse shocks are assoicated with a velocity jump but a number density, temperature and magnetic field decrease.) When a forward interplanetary shock encounters the magnetosphere the dynamic pressure, perforce, increases, the magnetopause moves inward, and magnetic flux is rearranged in the magnetosphere. In a vacuum magnetosphere we would see only a

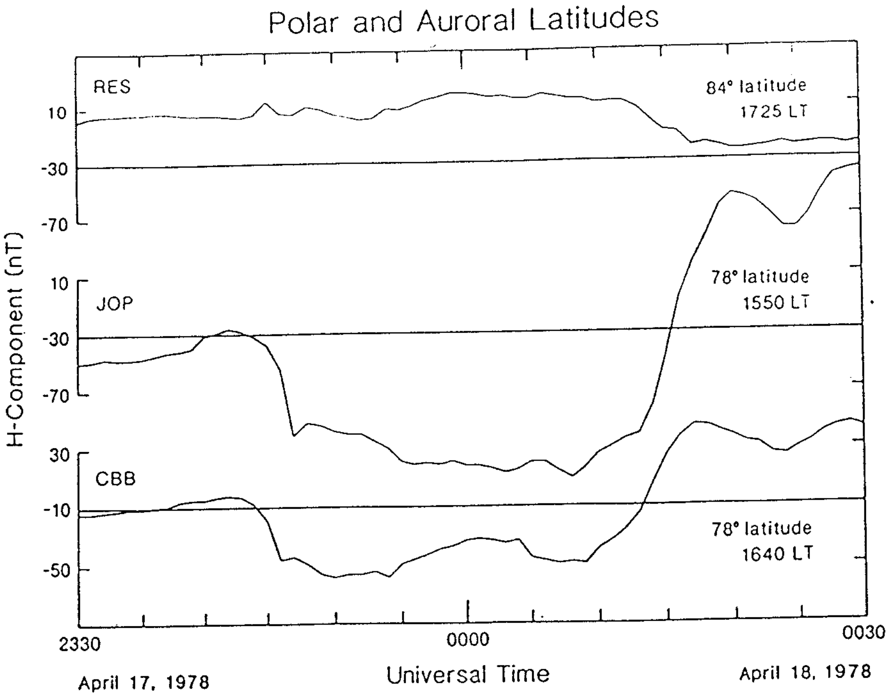

Fig. 4. High latitude response of the H-component of the ground-level magnetic field during the passage of the interplanetary shock shown in Figure 3. Observations from Resolute Bay, Johnson Point and Cambridge Bay are shown.

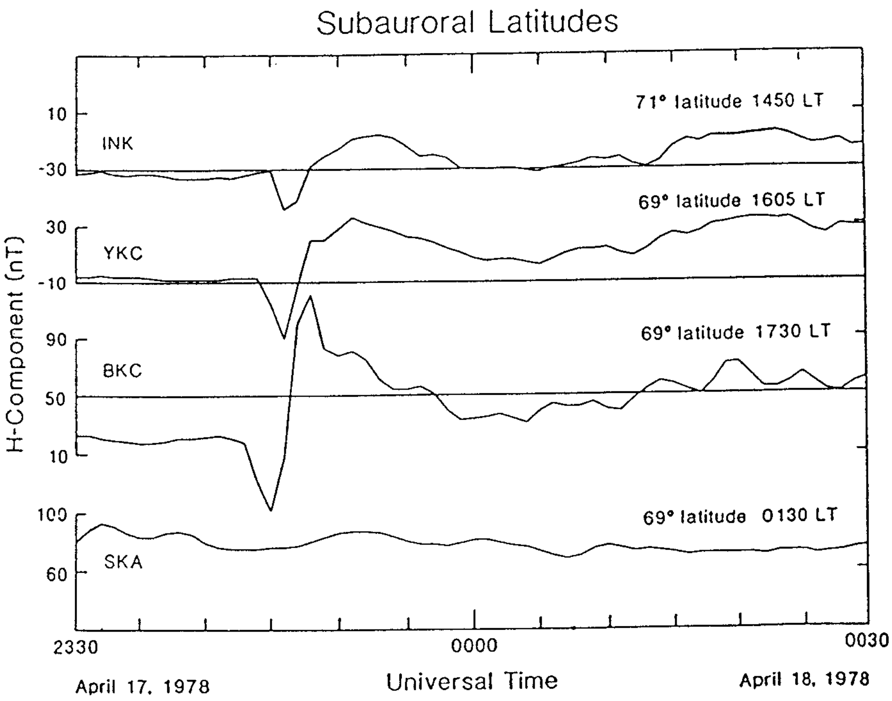

Fig. 5. Subauroral response of the H-component of the ground-level magnetic field during the passage of the interplanetary shock shown in Figure. Observations from Inuvik, Yellowknife, Back Bay and Sitka are shown.

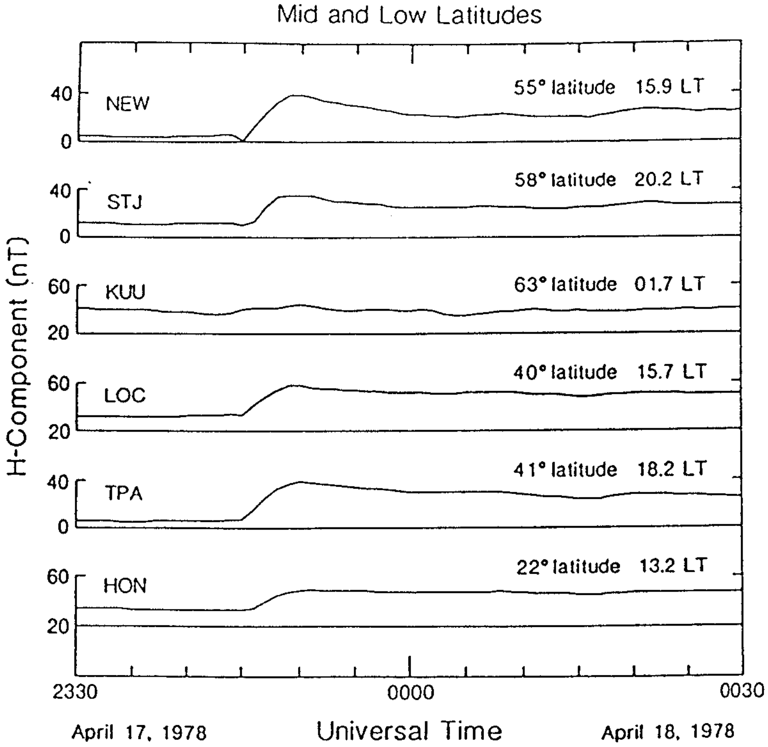

Fig. 6. Mid and low latitude response of the H-component of the ground-level magnetic field during the passage of the interplanetary shock shown in Figure 3. Observations from Newport, Saint Johns, Kuusamo, Lompoc, Tampa and Honolulu are shown.

compression of the magnetic field. In the terrestrial magnetosphere plasma currents are generated most noticeably under the equatorial electrojet and under the auroral electrojet where the Hall conductivity is large and currents become very sensitive to applied electric fields.

Figures 4, 5 and 6 show the response of ground station magnetic records, the horizontal or H-component, to the pressure increase shown in Figure 3. The greatest and most sustained response is at auroral latitudes as expected. At low latitudes there is some transient response which lasts a few minutes after the initial rise and then the disturbance reaches a steady state value. This transient is not due to currents interior to the Earth. An entirely perfectly conducting Earth would exclude all induced fields causing a 50% enhancement in the applied fields. The real Earth acts as if it were perfectly conducting, except over the outer 4% of its radius for periods of order hours [Chapman and Bartels, 1940]. Thus the enhancement of the field due to internal sources could decay only from an initial factor of 1.5 to a steady state value of 1.44, much smaller than evident at mid-latitudes. Hence the effect seen must be plasma related.

We have measured the change in solar wind dynamic pressure and the change in the surface magnetic field for a number of sudden impulses when the IMF was northward. The response on the ground is compared to the square root of the solar wind dynamic pressure change in Figure 7 [Russell et al., 1992] and compared with the Tsyganenko [1989a] prediction, increased

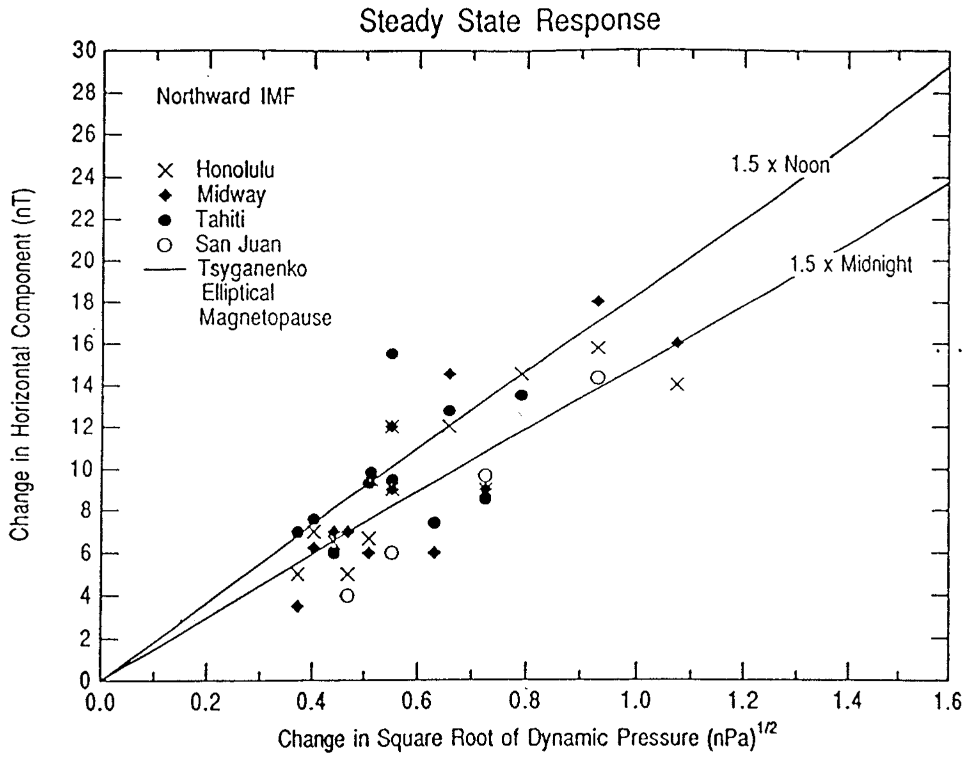

Fig. 7. Change in the horizontal component of the ground level magnetic field versus the change in the square root of the solar wind dynamic pressure. The solid lines show the theoretical response of the Tsyganenko [1989a] vacuum magnetosphere increased by 50% to take into account induced currents internal to the Earth. Only sudden impulses occurring when the IMF was northward are shown.

by 50% to account for the induced Earth currents. There is a lot of scatter but on average the Tsyganenko model with induced currents is a good predictor. This result is in contrast to the results of Siscoe et al [1968] who found very poor agreement with theory (see their Figure 3). While there are several points of departure between their work and ours, the major contributing factor was their use of a theoretical treatment that assumed an elastic solar wind interaction.

In plotting Figure 7 we chose data only from stations well away from the equatorial electrojet and the auroral electrojet to avoid the effects of these currents. Figure 8 shows a latitude profile of the normalized response of ground magnetic records during daylight hours from low latitudes to subauroral latitudes compared with the predicted latitude profile from the Tsyganenko [1989a] model. It is clear that stations from about 15° to 30° latitude are not affected by these additional plasma currents, but at lower and higher latitudes the response is enhanced and much more variable. The response in fact can be negative for a increase in the solar wind momentum flux. At night, as shown in Figure 9, the effect of these additional plasma currents is much less.

In summary, at low latitudes we can now quantitatively predict the size of the response to solar wind dynamic pressure changes for latitudes from about 15° to 30°. However, we have not yet examined the effect of southward magnetic fields on these results. The relative accuracy and repeatability of our present results is in contrast to earlier results without regard to station selection which ranged over a factor of 3 [Siscoe et al., 1968; Verzariu et al., 1972; Su and

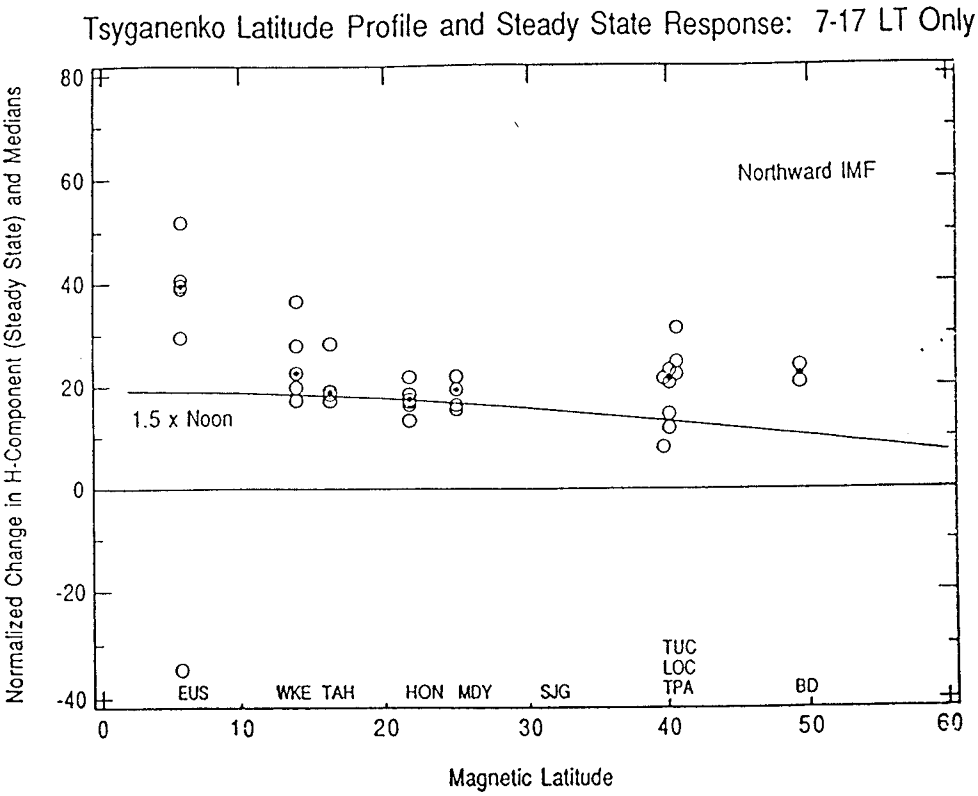

Fig. 8. Normalized response of the horizontal component of the ground-level magnetic field as a function of geomagnetic latitude for local times from 0700 to 1700. Median responses are shown by diamonds.

Konradi, 1975; Burton et al., 1975].

3. SURFACE RESPONSE AT SUBAURORAL LATITUDES

As the auroral oval is approached the effect of the auroral electrojet becomes more important and of the magnetopause currents relatively less. As a result the variations in field strength become both more rapid in time and more intense. This is particularly unfortunate for power distribution systems in the northeastern half of Canada and the United States which can become disrupted at times of intense activity [Albertson and Thorson, 1974]. They are particularly sensitive because the Earth's dipole is tilted in their direction so that they experience the effects of auroral current systems at a lower geographic latitude than experienced in other parts of the globe.

For the study of the these induced effects, a particularly useful set of data was obtained by the IGS network during the IMS [Stuart, 1982] and recently rehabilitated by Odera èt al. [1991]. The map on which these stations are plotted in Figure 10 indicates that the magnetic latitude of these stations spans the latitude range over which power disruptions have been observed in the US and Canada.

The response of these stations, as we will see below, is complicated because a variety of waves

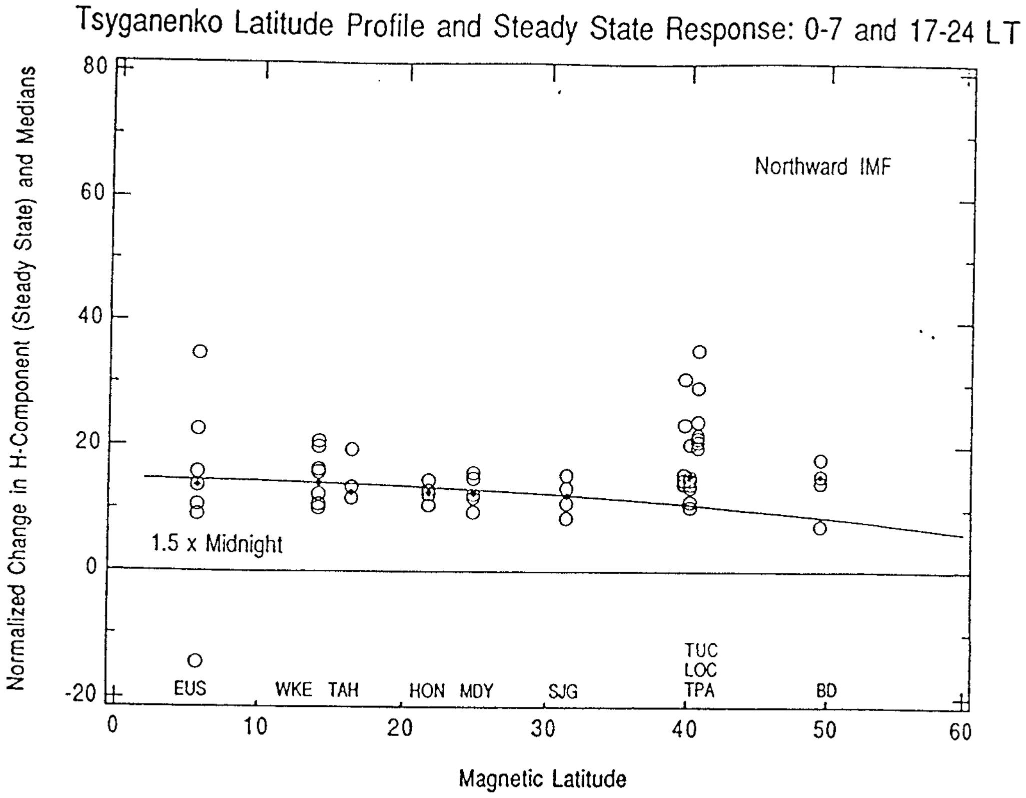

Fig. 9. Same as Figure 8 but for the remaining hours of the day.

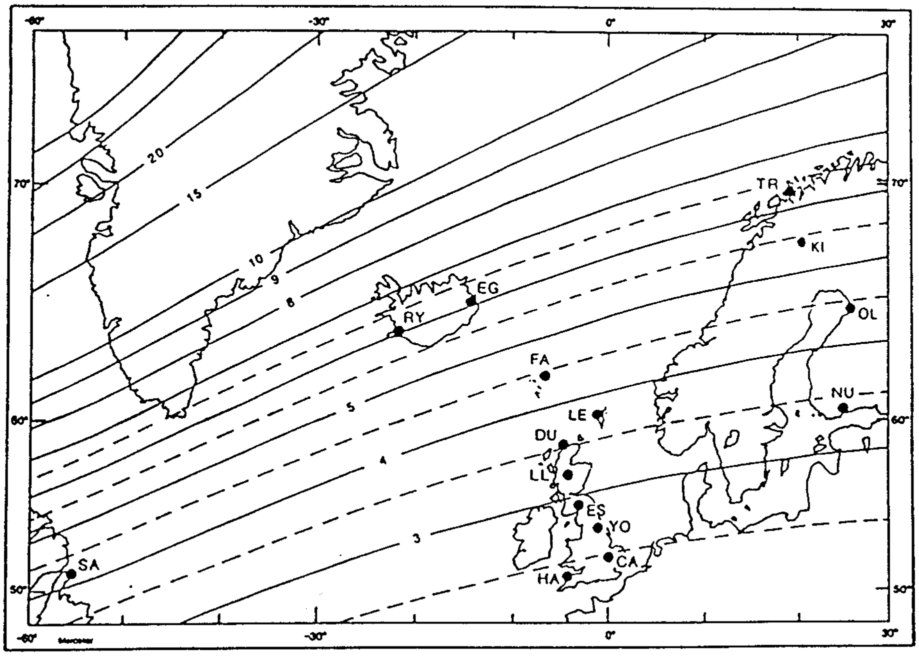

Fig. 10. The location of the magnetometer stations operated by the Institute of Geophysical Science (IGS) in Edinburgh [Stuart, 1983].

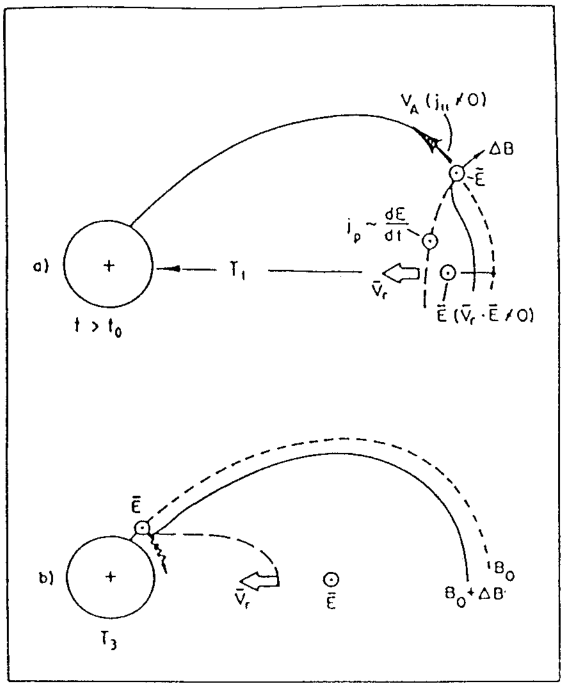

Fig. 11. Illustration of the expected response of the magnetosphere to a sudden pressure pulse. A wave is launched both along the magnetic field and across the magnetic field [Wilken et al., 1982]. It is thought that the field aligned part of the wavefront arrives first and is responsible for the preliminary impulse [Araki, 1977].

can propagate in the magnetosphere. An indication of this is shown in Figure 11 [Wilken et al. 1982]. In this picture a sudden compression of the magnetosphere launches both a compressional wave across field lines toward the Earth's equator and a shear Alfvén wave along magnetic field lines to the auroral ionosphere. The wave which causes the first ionospheric effect is not certain. Fast modes in general move faster than the Alfvén velocity and the fast mode has a shorter path. However, the density of plasma in the equatorial plane is much greater than along the auroral field lines and thus the Alfvén wave may arrive sooner.

In addition to being sampled over a range of latitude of intense interest to those concerned with geomagnetic effects on power distribution systems, the IGS array was sampled rapidly enough, every 2.5s, to resolve the principal magnetic field variations. These variations consist of a preliminary impulse followed by a main response [Araki, 1977]. The preliminary impulse is generally negative in the morning and positive in the afternoon and lasts a few tens of seconds at most. The main response can last many tens of minutes. Figure 12 shows how the amplitude of the two responses varies with local time normalized by the change in the square root of the solar wind dynamic pressure [Le et al., 1992a]. We note that this normalization is not as successful in ordering the high latitude data as at low latitudes. A possible reason depends principally on the Hall conductivity in the auroral ionosphere which in turn depends on the recent history of geomagnetic activity. We note that we have studied only times which the interplanetary magnetic field was northward so that the responses in Figure 12 should be due

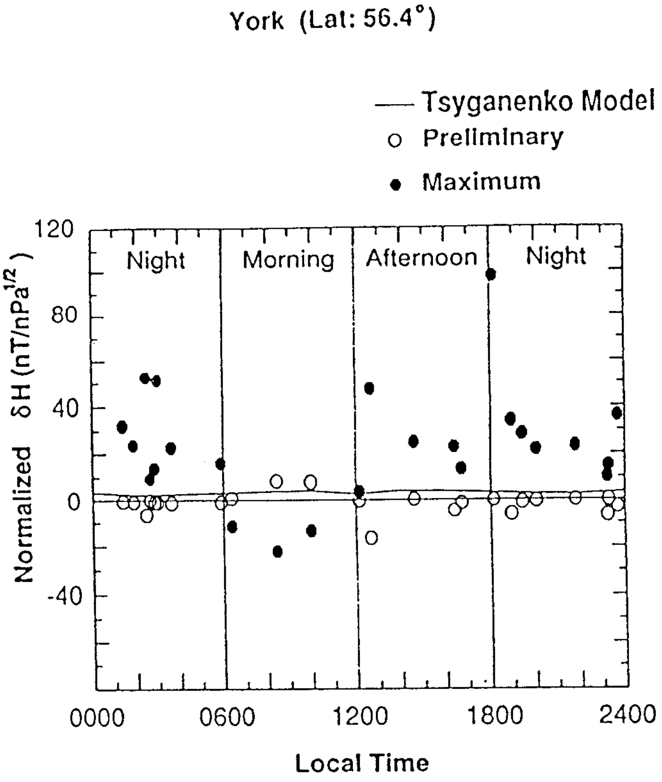

Fig. 12. The normalized response of a subauroral station (York) to sudden impulses, when the IMF was northward, plotted versus local time. Open circles show the size of the preliminary impulse. Solid circles show the size of the maximum response following the main onset. [Le et al., 1992].

principally to the dynamic pressure changes and not to triggered substorm activity.

One might expect that the strength of the disturbance was a function of geomagnetic latitude increasing with approach to the statistical auroral oval. However, this is not true in individual cases in which the strongest response may be at the lowest latitudes of the IGS chain, in the middle of the chain or at highest latitudes. The simultaneous response of the stations in the H component of the magnetic field is shown in Figure 13 for a typical event. [Le et al., 1992a]. Measuring the maximum disturbance and plotting its magnitude and horizontal direction on a projection of the polar cap shows the statistical response of these subauroral and auroral stations in Figure 14. The two largest events do occur at highest latitudes overall, but in individual cases the maximum can be at other latitudes. This figure also illustrates the coherence in response over the night and afternoon sectors contrasted with the "confusion" in the morning sector. For most of the day the maximum disturbance is roughly away from the pole but in the morning sector it is usually, but not always, poleward. This is illustrated more clearly in Figure 15 that shows the direction of current flow associated with each event. A clockwise current flow is seen over the night hemisphere and afternoon sector as seen from above the north polar cap. In the morning sector the current is principally in the opposite sense.

Of greatest interest to those concerned with power system disruptions is the rate of change of the magnetic field in these disturbances. These rates of change are being studied by Le et al.

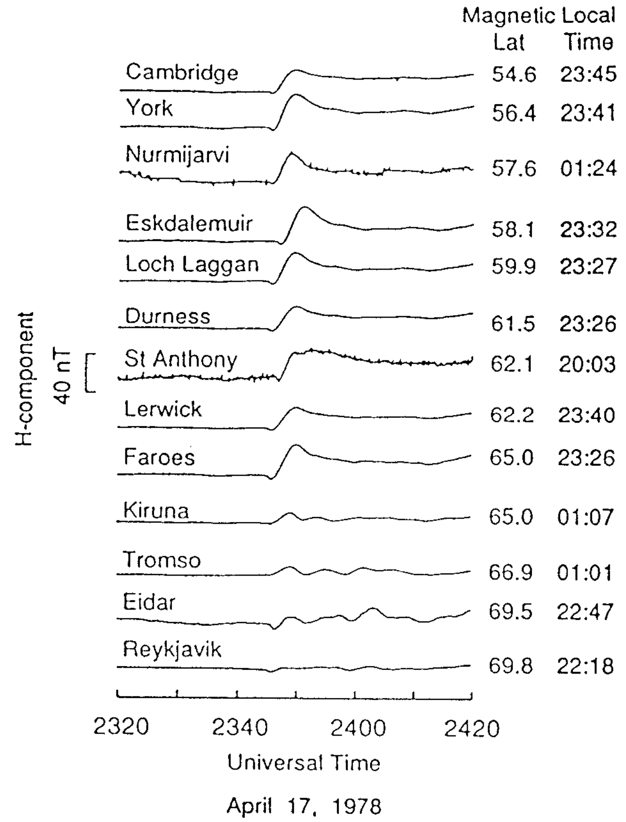

Fig. 13. Simultaneous H-component records from 13 auroral and subauroral stations of the IGS chain during a sudden impulse on April 17, 1978. [Le et al., 1992a].

[1992b] who finds that the disturbances here, none of which is known to have been associated with a power disruption, maximized at about 3 nT/s. Known disruptions have occurred at a level of about 7 nT/s. [J. Joselyn, personal communication, 1992].

4. THE SIZE OF THE MAGNETOSPHERE

As discussed in the introduction to this paper, the solar wind dynamic pressure determines the size of the magnetosphere. Petrinec et al. [1991] have studied the size of the magnetosphere over the last solar cycle, cycle 21. As illustrated in Figure 16, the size of the magnetosphere, as measured by the radius of the nose of the magnetosphere, varies during the solar cycle as the solar wind dynamic pressure varies. Perhaps it is important to note that during solar cycle 21, the average nose distance for northward IMF was 10 R_e and for southward field about 0.5 R_e less, while during solar cycle 20 the average location was about 11 R_e. [Fairfield, 1971]. Thus the magnetosphere has become significantly smaller in recent years. The reason for this is illustrated in Figure 17 which shows the variation in solar wind dynamic pressure as measured by solar wind instruments whose data have been submitted to the NSSDC [J. King, personal communication, 1991]. The solar wind clearly has changed most significantly in the years its has been monitored. It is not varying simply in a periodic fashion over the solar cycle.

As noted above, the size of the magnetosphere depends on the direction of the interplanetary

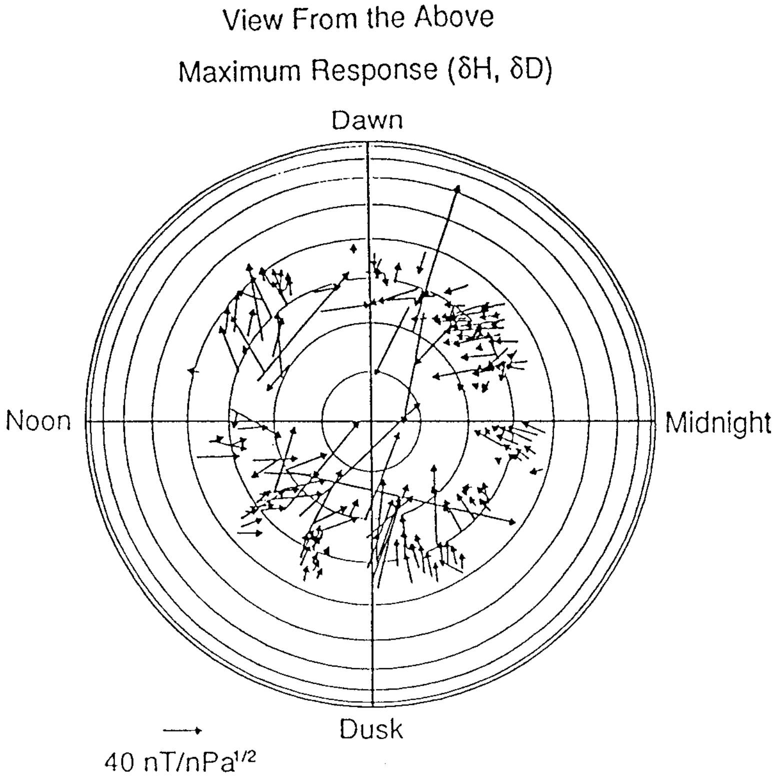

Fig. 14. Maximum post-onset response of the IGS chain during sudden impulses with the IMF northward. Two dimensional (H, D) disturbance vectors are plotted on a latitude-local time polar grid. Latitude grids are shown every 10 degrees.

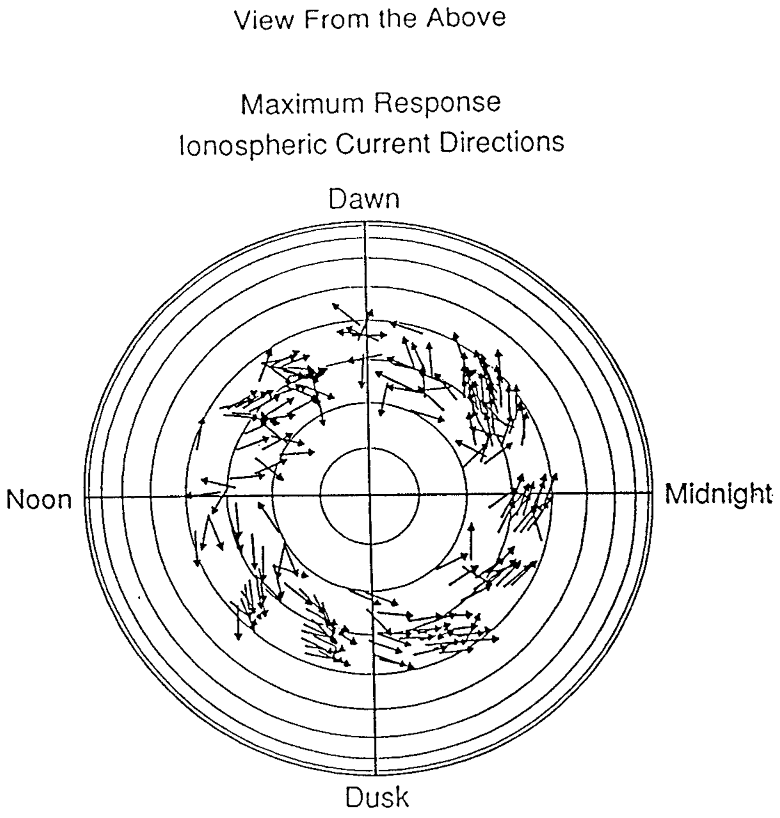

Fig. 15. Directions of currents consistent with the disturbance vectors shown in Figure 15. Same grid is used.

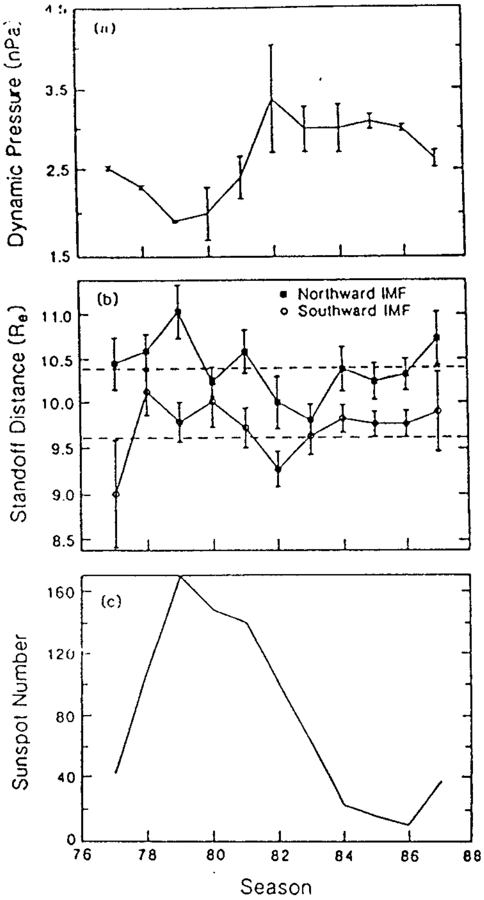

Fig. 16. Dynamic pressure of the solar wind (top); location of the magnetopause when the IMF was northward and southward (middle) and the sunspot number during solar cycle 21 as measured by the ISEE spacecraft.

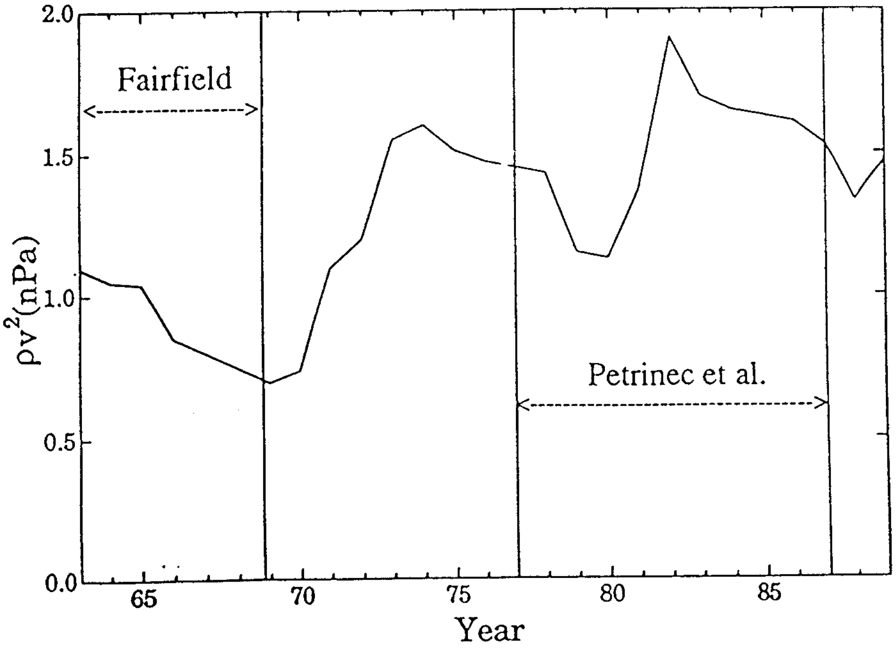

Fig. 17. Dynamic pressure variation of the solar wind from 1963 to 1989 as measured by the spacecraft whose data have been submitted to the National Space Science Data Center [J. King, personal communication, 1991].

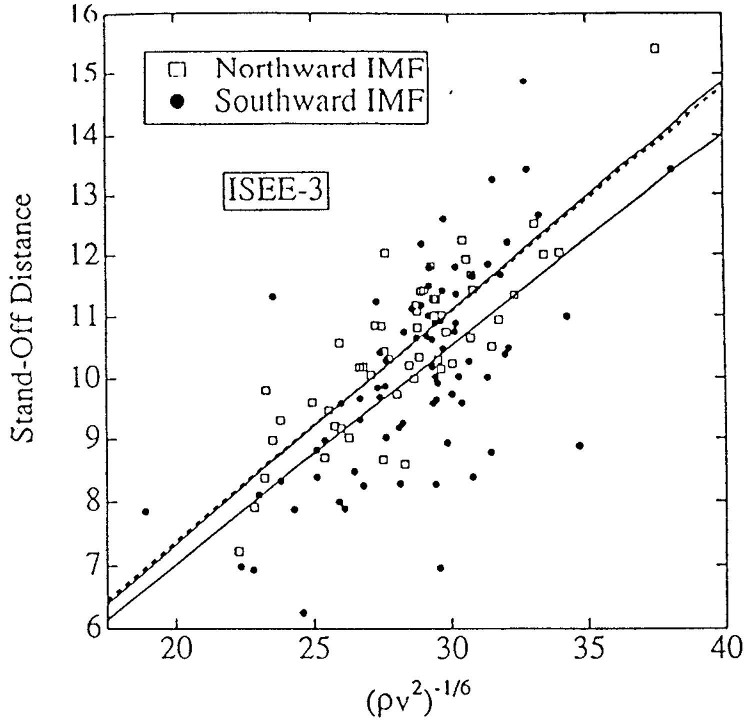

Fig. 18. Distance to the nose of the magnetosphere as a function of the inverse sixth root of the solar wind dynamic pressure using ISEE-3 data corrected for the average helium abundance of the solar wind. The dashed lines show the expected position according to the Tsyganenko [1989a] model. The two solid lines show the least square fits for northward and southward IMF.

magnetic field. When the interplanetary magnetic field is southward the magnetic field of the solar wind reconnects with the magnetospheric field, erodes magnetic flux from the dayside of the magnetosphere and transports it to the tail. This erosion makes the magnetosphere smaller [Aubry et al., 1970]. The effect of this erosion process is shown for all levels of dynamic pressure in Figure 18. [Petrinec and Russell, 1992]. Here we plot the position of the nose of the magnetosphere as a function of the negative sixth root of dynamic pressure including the contribution of the observed solar wind Helium density. We plot the locations of the magnetopause for clearly northward and clearly southwood IMF separately. If we compute where the subsolar magnetopause should be for varying solar wind dynamic pressure as discussed in the introduction assuming an inelastic solar wind and the correction for the divergence of the magnetosheath streamlines we obtain the theoretical line shown. It is in very good agreement with our observed dependence for northward fields. Our "southward" magnetopause crossings are 0.5 R_e closer.

The erosion of the magnetopause is not a binary process, zero for northward and 0.5 R_e for southward but depends on how southward is the IMF. This is illustrated in Figure 19 which shows the how the magnetopause shrinks as the southward component of the IMF grows larger. [Petrinec and Russell, 1992]. When the IMF is 10 nT southward, the magnetopause can be 2 R_e inward of its northward location. When the IMF is northward the magnetopause location seems to be roughly independent of the north-south field component. This is in contrast to the

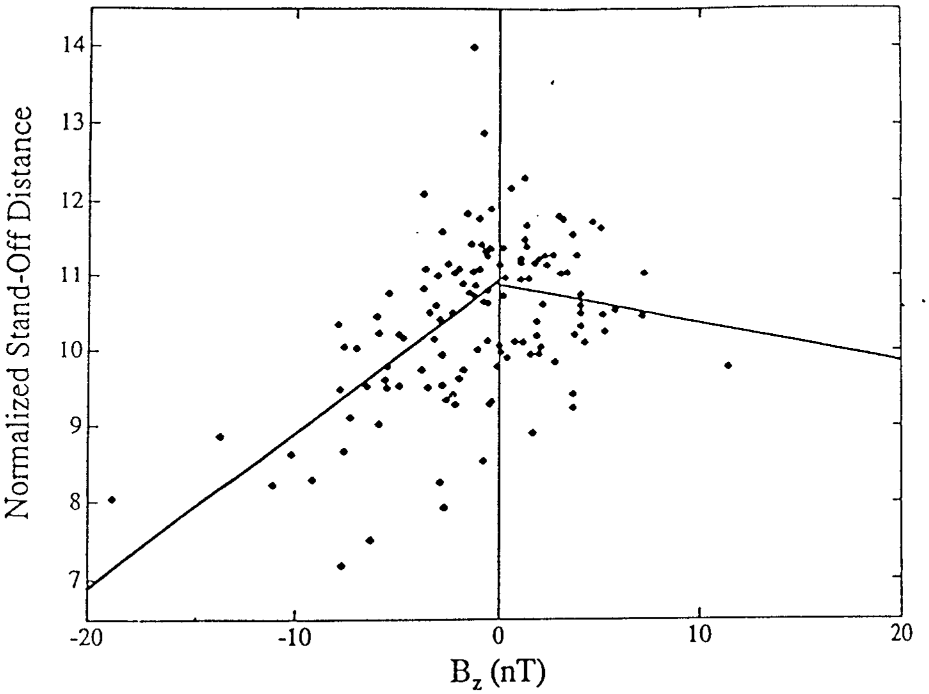

Fig. 19. The normalized location of the nose of the magnetopause corrected for solar wind dynamic pressure plotted against the north-south component of the IMF in magnetospheric coordinates. [Petrinec and Russell, 1992].

work of Sibeck et al. [1991] who used hourly averages which are long compared to the time for IMF change and magnetospheric response.

External factors are not alone in determining the size of the magnetosphere. There is plasma in the magnetosphere, a variable amount of plasma, whose energy content can enhance the pressure of the magnetic field. We can measure the energy content of the magnetospheric plasma with the Dst index which measures the deviation of the H-component from quiet day values for a global network of low latitude stations [Dessler and Parker, 1959]. Figure 20 shows this effect for northward IMF in the top panel, and for southward IMF in the middle panel. When the IMF is southward the magnetopause is eroded so we might expect the expansion of the magnetosphere caused by the ring current might be masked somewhat and so it appears to be. In the bottom panel we show the same data as in the middle panel but corrected for the erosion of the magnetopause by southward IMF as illustrated in Figure 19. As expected this correction shows that ring current effect is the same size and in the same sense for both sets of data. Increasing ring current inflates and expands the magnetosphere. With the tools we have, we should soon be in position to predict not only the size of the magnetosphere but also the magnetic field strength within the magnetosphere.

5. SUMMARY AND CONCLUSIONS

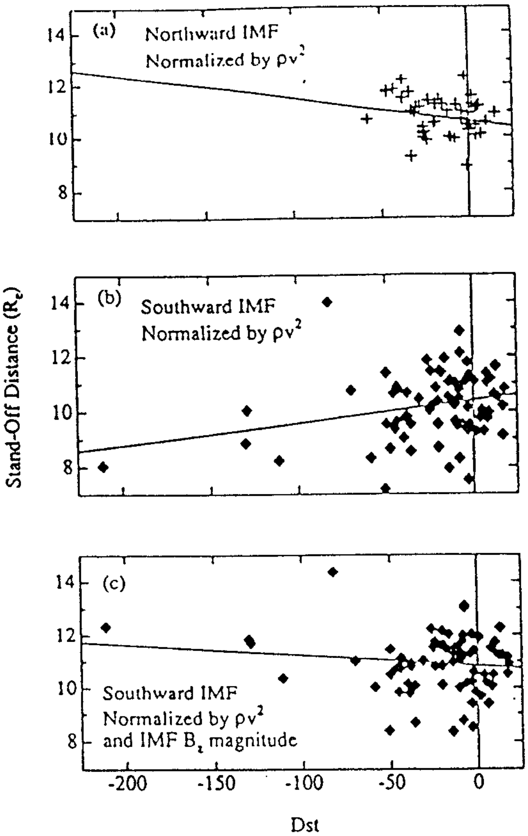

Fig. 20. The normalized location of the magnetopause as a function of the strength of the ring current as measured by Dst for northward IMF (top); for southward IMF (middle) for southward IMF adjusted for erosion effects as given in Figure 19. [Petrinec and Russell, 1992].

The solar wind dynamic pressure controls the size of the magnetosphere. Interplanetary shocks in turn cause rapid changes in that dynamic pressure. When this rapid increase in dynamic pressure envelops the magnetosphere, it rapidly shrinks, and the field on the surface of the Earth rapidly increases. In the equatorial auroral zones the response is enhanced by the Hall conductivity of the ionosphere. Here the response is magnified and somewhat unpredictable. At low latitudes away from the equatorial electrojets, we can predict the enhancement quite well.

Two other factors are important in determining the size of the magnetosphere. Erosion by reconnection associated with southward IMF shrinks the dayside magnetosphere and changes its shape. Inflation of the magnetosphere by the energetic plasma of the ring current increases the size of the magnetosphere. We now know how to quantify these effects.

Finally, we should stress that while we understand how to predict that response of the magnetosphere given the observed properties of the solar wind, we do not know how to predict how those properties are going to evolve on short or long scales. We have evidence over the last 3 solar cycles that major changes can occur in the solar wind with decade time scales. The dynamic pressure of the solar wind has changed markedly in the last 30 years. Moreover, the magnetic field of sunspots has also changed markedly during this period [J. H. Allen, personal communication, 1991]. This could lead to more intense solar flares and perhaps to more intense interplanetary shocks.

6. ACKNOWLEDGMENTS

We wish to thank J. H. King for allowing us to publish his compilation of solar wind dynamic pressures in Figure 17. This work was supported by the National Science Foundation under research grants ATM 90-16900 and ATM 91-11913.

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