GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO. 11, PAGES 1015-1018, JUNE 7, 1993

SUDDEN IMPULSES AT LOW LATITUDES: TRANSIENT RESPONSE

C. T. Russell and M. Ginskey

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

Abstract. When the magnetosphere is compressed by a sudden change in the solar wind dynamic pressure, the horizontal component of the Earth's magnetic field is increased at low latitudes. Often there is an overshoot associated with this increase in the field, but not always. The overshoot does not appear to be due to induced currents in the interior of the Earth or in the ionosphere. Rather, its magnitude appears to be controlled by both the strength of the ring current, and by local time. We speculate that the overshoot in the horizontal component is due to an overshoot in the compression of the magnetosphere and that when the ring current is strong the compressional wave is damped and the magnetosphere is not set into oscillation by the compressional wave.

Introduction

The size of the magnetosphere is controlled principally by the solar wind dynamic pressure [see for example recent papers by *Petrinec et al.*, 1991 and *Sibeck et al.*, 1991]. Its shape is determined by several factors, including the southward component of the interplanetary magnetic field [*Russell and McPherron*, 1973; *Petrinec et al.*, 1991]. The response of the ground level magnetic field to a sudden increase in the solar wind dynamic pressure is complex. At auroral and subauroral latitudes there is both a preliminary impulse lasting seconds and a later main response in which the field is enhanced or depressed for many tens of minutes [*Araki*, 1977; *Le et al.*, 1993]. Since this latter response has a longer duration than the travel time of the solar wind past the dayside magnetosphere or the bounce time of waves along closed field lines we associate this main response with ionospheric convection patterns set up to establish a new ground state for the magnetosphere, e.g. for the feet of compressed flux tubes to move to new equilibrium positions and for the magnetospheric plasma to establish a new corotational pattern.

The steady state response of the magnetosphere to a change in the dynamic pressure in the solar wind is qualitatively well understood. A portion of the momentum flux of the solar wind is converted to thermal and magnetic pressure in the magnetosheath which in turn apply a normal stress on the magnetopause. This normal stress determines both where the magnetopause is located and the strength of the currents flowing on it. Due to the divergence of stream tubes in the magnetosheath, this stress is about 88% of the solar wind momentum flux at the subsolar point *(Spreiter et al.*, 1966). On the magnetospheric side this stress is balanced by the compressed magnetospheric magnetic field. The amount of this compression varies with the shape of the magnetopause. For a planar magnetopause this factor is 2 at the subsolar point, for a spherical magnetopause it is 3, and for a realistically shaped magnetopause it is 2.44 at the subsolar point (*Russell et al.*, 1992).

The field measured on the surface of the Earth is a combination of the field due to interior and exterior sources. For temporally varying sources, currents are induced that exclude the field from the interior. *Chapman and Bartels* (1940) find that these currents (at periods of 1 day) flow effectively at 0.96 Earth radii (R_E) and increase the field on the surface by 44%. The net result is that the field on the surface of the Earth changes about 16.5nT for each change of 1 $(\mathrm{nPa})^{1/2}$ of solar wind dynamic pressure [*Russell et al.*, 1992]. This value depends on both local time and latitude to a certain extent as well. At night the magnetopause currents are further away and thus have a weaker effect than on the dayside, but the tail currents, that generate fields opposite to the field due to the compression of the magnetopause, are closer.

At very low latitudes the currents of the equatorial electrojet affect the ground level response during daytime hours and at mid to high latitudes the currents in the auroral ionosphere affect the ground level response. As a result there is apparently only a limited range of magnetic latitudes, about 15 to 30°, where the stations are principally responsive to the magnetopause and tail current systems.

In this study we continue our examination of the response of these stations but turn to the transient or overshoot response. We will not concern ourselves with the more rapid preliminary increase or decrease seen at higher latitudes [*Araki*, 1977]. That phenomenon has been treated elsewhere [*Le et al.*, 1993].

Observations

In order to measure the ground level response to sudden changes in the solar wind dynamic pressure (shocks) we use digital records obtained during the International Magnetospheric Study (IMS) and shortly thereafter at Honolulu, Tahiti, and Midway [*Russell*, 1987]. We use digital records because we can measure the changes in field strength most accurately with these records. Moreover, we can replot and rescale the data as needed. In our data base we identified 15 interplanetary shocks when the IMF was clearly northward before and after the shock passage. We had digital data across the sudden impulses produced by these shocks at our 3 stations a total of 37 times. Figures 1 and 2 show records from these stations as well as from Wake and Lompoc together with measurements in the solar wind on August 18, 1978 and January 25, 1980. On the first day the overshoot is clearly not present at any of the stations and on the second it is clearly present at all of the stations. After about 5 minutes following the peak response the overshoot has disappeared. The ISEE-3 and IMP-8 solar wind data used here have been recalibrated so that all dependences of the electron to ion density ratio on the ion velocity and temperature have been removed [*Petrinec and Russell*, 1993].

The origin and variability of the low latitude overshoot are puzzling. Since it is not always present, it cannot be due to currents in the interior of the Earth. Even if it were always present, it could not be due to an interior source because the largest possible induced field effect is a 50% increase in the

Paper number 93GL01257
0094-8534/93/92GL-01257$03.00

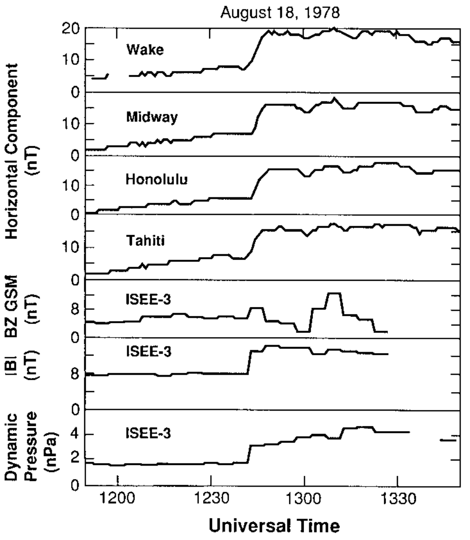

Fig. 1. The change in the horizontal component of the Earth's magnetic field at Wake, Midway, Honolulu and Tahiti on August 18, 1978 in response to the passage of an interplanetary shock wave detected by ISEE-3. Observations from Wake were not used in the statistical study because of its proximity to the equatorial electrojet. The bottom three traces show the Z-solar magnetospheric component of the interplanetary field,the strength of the magnetic field and the solar wind dynamic pressure. The interplanetary data have been aligned with the terrestrial data to remove the expected time delay associated with the propagation of the interplanetary shock. The interplanetary magnetic field was northward before and after the shock passage.

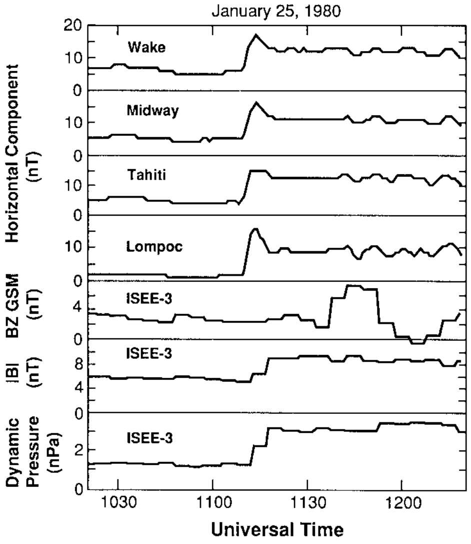

Fig. 2. The change in the horizontal component of the Earth's magnetic field at Wake, Midway, Tahiti and Lompoc on January 25, 1980, in response to the passage of a interplanetary shock detected by ISEE-3. Observations from Lompoc were not used in the statistical study because of its possible sensitivity to auroral zone currents. See caption of Figure 1.

field which would arise, if there were no penetration of the field below the Earth's crust, while the long period enhancement due to induced currents is 44% [*Chapman and Bartels*, 1940]. At most the decaying currents in the Earth's crust could account for the differences in these two values and make an overshoot of a few percent. Since the overshoot is much bigger than this, the source of the overshoot must lie in some magnetospheric or ionospheric process.

Control by Dynamic Pressure

One would expect that, if the overshoot illustrated in Figure 2 was at all associated with the pressure change which caused the steady state response, one would find that the size of the overshoot would be correlated with the dynamic pressure jump. However, since the overshoot is not always present, this correlation should be a weak one. To measure the magnitude of the overshoot, we extrapolate the trend in the H-component prior to the sudden impulse and then measure the maximum difference between the extrapolated baseline and the H-component trace. Figure 3 shows the size of the overshoot plotted versus the change in the square root of the solar wind dynamic pressure. The line drawn is the median slope of the overshoot responses plotted. It divides the observations in half and passes through the origin. The correlation coefficient of the best fit straight line (not shown) is 0.65. Figure 4 shows the size of the overshoot plotted versus the size of the steady state response which we have shown elsewhere [*Russell et al.*, 1992] to be responsive to the change in the square root of the solar wind dynamic pressure. The points are enclosed by 2 straight lines with slopes of 1 and 2. Both Figures 3 and 4 show much scatter but it is clear that there is an overall statistical increase in the size of the overshoot as the jump in pressure becomes larger. We recall that our study includes only cases with northward IMF in order to avoid transient currents associated with substorms and dayside reconnection.

The large scatter in these 2 figures and the frequent absence of an overshoot as indicated by the points along the line of unit slope in Figure 4 again indicates that there is another important controlling factor. One such factor might be the local time of the observations. We show the transient response as a function of local time in Figure 5. The

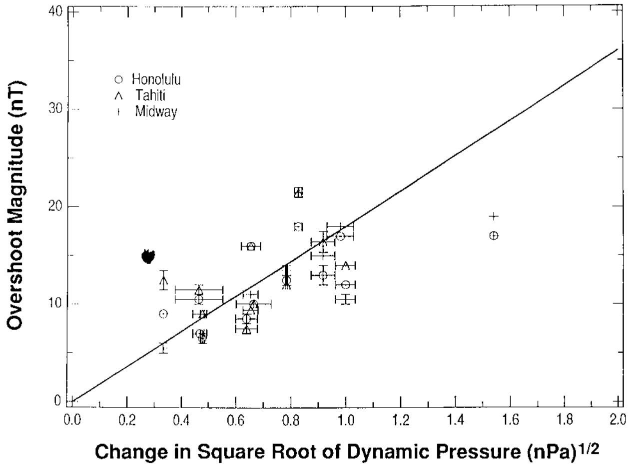

Fig. 3. The change in the horizontal component of the magnetic field from its extrapolated preshock value to its post shock maximum as a function of the change in the square root of dynamic pressure of the solar wind. The line drawn has a slope of $18 nT/(nPa)^{1/2}$ and is the median slope of the response of these stations. The error bars show our estimates of the errors in the measurements.

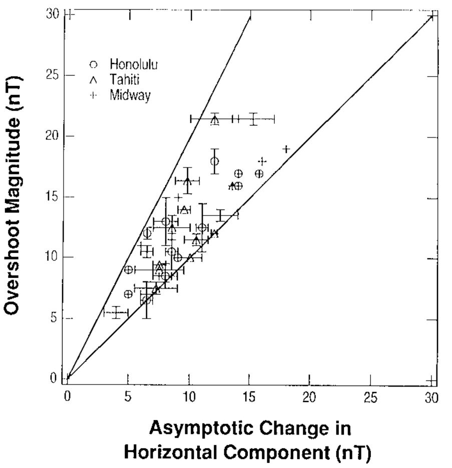

Fig. 4. The change in the horizontal component of the magnetic field at Honolulu, Tahiti and Midway from the extrapolated pre-shock valued to the maximum post-shock value as a function of the steady state response to the shock passage. The lines drawn have slopes of 1 and 2. The error bars shows our estimate the error in each measurement.

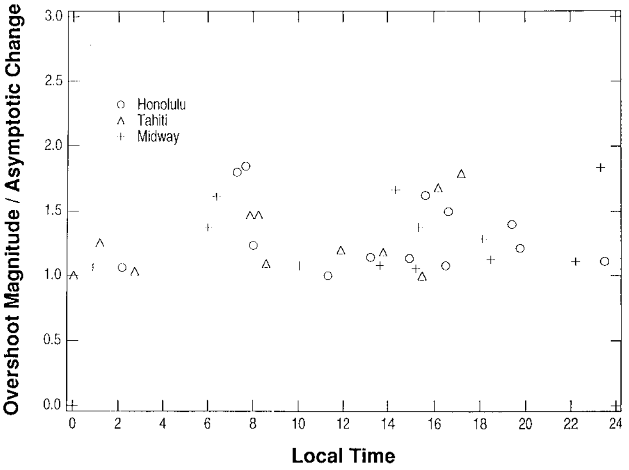

Fig. 5. The local time variation of the ratio of the transient response to the steady state response.

overshoots seem to be generally small near noon and at night and have variable amplitudes just before dawn and dusk. The weakness near noon where ionospheric conductivity is high suggests that the overshoot is not due to an ionospheric current. We have also examined the correlation with the F10.7 cm solar flux index which measures the activity of the sun and also find no control of the magnitude of this effect. Again this indicates that the overshoot is not due to currents in the ionosphere.

Ring Current

The ring current is the next major reservoir of plasma in the magnetosphere above the ionosphere. While much less dense than the ionosphere, it often contains a much greater total energy than the ionosphere and its extension into space, the plasmasphere, and hence plays an important role in magnetospheric current systems. Moreover, the ring current is quite variable in strength and thus is a candidate to explain the otherwise mysterious variability of the overshoot. Perhaps, the ring current in some way stabilizes the magnetosphere and does not allow the formation of the overshoot.

In order to calculate the ring current strength we use the Dst index and normalize it to a standard (zero) solar wind dynamic pressure by removing the average of the daytime and nighttime response to solar wind dynamic pressure changes (14.4 nT times the square root of the dynamic pressure change in $nPa^{1/2}$ [*Russell et al.*, 1992]). This correction factor is averaged over all local times and is appropriate for measurements that include the helium content of the solar wind. Figure 6 shows the size of the overshoot divided by the steady state response versus the strength of the ring current for local times from 0600-1000 and 1400-1800. There is still much scatter, perhaps in part because of our inability to perfectly measure the strength of the ring current through the Dst index. To test our hypothesis of the importance of the ring current we divide our observations into two groups: those with little or no overshoot ($<$ 20%) and those with measurable overshoot ($>$20%) and calculate the mean Dst*. For the former group, the average and probable error of the mean are -44 ± 9nT. For the latter group, the average is -19 ± 3nT. Thus, the data suggest that when the ring current is strong (very negative Dst index) there is no overshoot.

Discussion

Our interpretation of the overshoots, lasting several minutes in the H-components of low latitude magnetograms, is that they are formed by a compression of the magnetopause which itself overshoots its post-shock equilibrium position before returning to its steady state location. We base this interpretation in part on our previous work showing that the change in the H component at low latitude stations was as predicted from magnetopause currents alone with no contribution from equatorial or high latitude currents [*Russell et al.*, 1992]. This interpretation is consistent with earlier work in which overshoots in the magnitude of the field have been observed at large radial distances in the dayside magnetosphere showing that the overshoot is a magnetospheric as opposed to an ionospheric (or plasmapause) phenomenon [*Zhuang et al.*, 1981; *Kokubun*, 1983], and with the observation on at least one occasion of the rebound of the magnetosphere after the passage of an interplanetary shock [*Zhuang et al.*, 1981]. The proposed ring current effect on this magnetospheric overshoot to our knowledge has not previously been suggested.

The response of the magnetosphere to a sudden

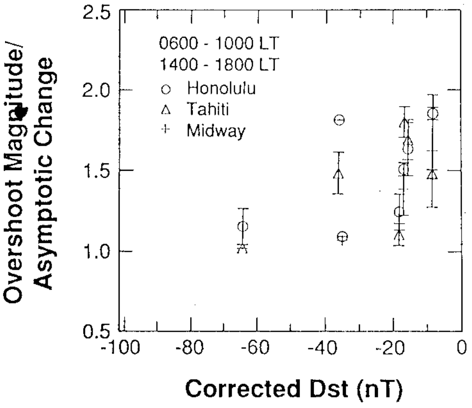

Fig. 6. The Dst variation of the ratio of the transient response to the steady state response. Dst has been corrected to zero solar wind dynamic pressure to better reflect the strength of the ring current.

compression by the solar wind is surprisingly complex even when care is taken to avoid substorm effects. At the shortest periods, seconds, is the preliminary response studied by *Araki* [1977]. We interpret this to be the arrival of field aligned Alfven waves at high latitudes caused by the distortion of the distant magnetosphere. Next comes the compression of the magnetosphere discussed herein for which the rise time is determined by the length of time required to compress the entire frontside magnetosphere and communicate that compression to the ground, which time is several minutes. An overshoot occurs in our interpretation if the magnetosphere becomes overcompressed in this process. One would expect the magnetosphere to be most elastic when it is devoid of energetic plasma. Times of low ring current intensity would be such a time. When the ring current intensity was high, the energy of the compressional wave might be damped and the wave not reverberate in the magnetosphere. This damping might take place through the betatron and Fermi acceleration during the compression of the magnetosphere.

While the flux tubes can be compressed rapidly their ionospheric footpoints cannot move so rapidly and may take tens of minutes to adjust. We attribute this readjustment to be the cause of the twin vortex currents which give depressions and enhancements in the field on the dawn and dusk sides of the magnetosphere and which exponentially decay away in about 10-20 minutes [*Araki*, 1977]. This is not the complete story, however, because at mid and high latitudes almost always the field reaches an enhanced level for the order of an hour well above that due to magnetopause currents alone [*Le et al.*, 1993]. We attribute these world wide circumpolar currents to the establishment of a new corotational regime in the magnetosphere. Conservation of angular momentum during the compression of the magnetosphere causes the cold plasma in the outer magnetosphere to spin faster than the Earth and its ionospheric plasma. Injection of plasma from the ionosphere into the magnetosphere by Joule heating at the base of flux tubes would result in plasma moving too slowly that needed to be accelerated by the ionosphere. This speculation, of course, should be tested with measurements of the corotational history of the plasmasphere after a sudden impulse.

Conclusions

At low latitudes the transient response of ground stations to the sudden change of the solar wind dynamic pressure is quite variable. The amplitude of the overshoot in the magnetic field near the beginning of the sudden impulse varies markedly from event to event. The size of the overshoot is too large to be due to currents induced in the Earth and the variability in the overshoot is incompatible with such a source. The fact that the effect disappears both near noon and midnight and is independent of the F10.7 cm flux also suggests that the current system and its control lie above the ionosphere. The ring current amplitude, on the other hand, does appear to control the overshoot. We can only speculate on how this control occurs. It is not obvious to us why the size of the transient response varies with the local time. We urge those with MHD models of the magnetosphere to attempt to simulate this effect.

Acknowledgments. The authors are grateful for the assistance of S. M. Petrinec in preparing the corrected files of solar wind data and advice on other aspects of the study. The authors also wish to thank T.Araki for many helpful suggestions in the courses of this study. This research was supported by the National Science Foundation under grant ATM90-16900.

References

Araki, T., Global structure of geomagnetic sudden commencements, *Planet. Space Sci., 25*, 373-384, 1977.

Chapman, S. and J. Bartels, *Geomagnetism,* Oxford, London, 1940.

Kokubun, S., Characteristics of sudden storm commencement at geostationary orbit, *J. Geophys. Res., 88*, 10025-10033, 1983.

Le, G., C. T. Russell, S. M. Petrinec, and M. Ginskey, Effect of sudden solar wind dynamic pressure changes at subauroral latitudes: Change in magnetic field, *J. Geophys. Res., 98*, 3983-3990, 1993.

Petrinec, S. M. , P. Song, and C. T. Russell, Solar cycle variations in the size and shape of the magnetopause, *J. Geophys Res., 96*, 7893-7896, 1991.

Petrinec, S. M. and C. T. Russell, The intercalibration of solar wind instruments during the IMS, *J. Geophys. Res.*, submitted, 1993.

Russell, C. T., Increasing the accessibility of IMS magnetograms, *EOS, 68*, 1601, 1987.

Russell, C. T. and R. L. McPherron, The magnetotail and substorms, *Space Sci. Rev., 15*, 205-266, 1973.

Russell, C. T., M. Ginskey, S. Petrinec, and G. Le, The effect of solar wind dynamic pressure changes on low and mid-latitude magnetic records, *Geophys. Res. Lett., 19*, 1227-1230, 1992.

Sibeck, D. G., R. E. Lopez, and E. C. Roelof, Solar wind control of the magnetopause shape,location and motion, *J. Geophys. Res., 96*, 5489-5495, 1991.

Zhuang, H. C., C. T. Russell, E. J. Smith and J. T. Gosling, Three-dimensional interaction of interplanetary shock waves with the bow shock and magnetopause: A comparison of theory with ISEE observations, *J. Geophys. Res. 86*, 5590-5600, 1981.

M. Ginskey and C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024-1567.

(Received December 11, 1992;
revised April 2, 1993;
accepted April 23, 1993.)