A FLOOR IN THE SOLAR WIND MAGNETIC FIELD

L. SVALGAARD
Easy Tool Kit, Inc., Houston, TX 77055-7010
AND
E. W. CLIVER
Space Vehicles Directorate, Air Force Research Laboratory, Hanscom AFB, MA 01731-3010

ABSTRACT

Long-term (~130 years) reconstruction of the interplanetary magnetic field (IMF) based on geomagnetic indices indicates that the solar wind magnetic field strength has a "floor," a baseline value in annual averages that it approaches at each 11 yr solar minimum. In the ecliptic plane at 1 AU, the IMF floor is ~4.6 nT, a value substantiated by direct solar wind measurements and cosmogenic nuclei data. At high heliolatitudes, *Ulysses* measured a constant radial field with a magnitude (normalized to 1 AU) of ~3.2 nT during solar minimum conditions in ~1995 when the observed solar polar fields were ~100 μT and in 2006 when the polar fields were ~60 μT, as well as for solar maximum conditions in 2001 when the polar fields were close to zero. We identify the floor with a constant (over centuries) baseline open magnetic flux at 1 AU of ~4 × 10^{14} Wb, corresponding to a constant strength (~10^{11} A) of the heliospheric current. Solar cycle variations of the IMF strength ride on top of the floor. The floor has implications for (1) the solar wind during grand minima—we are given a glimpse of Maunder minimum conditions at every 11 yr minimum; (2) current models of the solar wind—both source surface and MHD models are based on the assumption, invalidated by *Ulysses*, that the largest scale fields determine the magnitude of the IMF; consequently, these models are unable to reproduce the high-latitude observations; and (3) the use of geomagnetic input data for precursor-type predictions of the coming sunspot maximum—this common practice is rendered doubtful by the observed disconnect between solar polar field strength and heliospheric field strength.

Subject headings: interplanetary medium — solar wind — Sun: magnetic fields

1. INTRODUCTION

Svalgaard & Cliver (2005) used their newly derived interdiurnal variability (IDV) geomagnetic index to obtain a relationship between yearly averages of the solar wind magnetic field (B) in the ecliptic plane and the square root of the annual sunspot number (Wang & Sheeley 2005):

$$B(\text{nT}) = (0.273 \pm 0.015)R^{1/2} + (4.62 \pm 0.16) \quad (r = 0.84).$$
$$(1)$$

This equation is based on 12 solar cycles of measured or inferred (from IDV) solar wind B. The IDV index is strongly correlated with B and can be used to infer B from ground-based measurements of geomagnetic variations. In this study we focus on the constant term in equation (1), corresponding to $R = 0$, where R is the sunspot number (SSN). We suggest that this term represents a baseline state or "floor" of the solar wind magnetic field, constant in both time and space, on which the variable SSN-dependent component sits.

In § 2 we compile supporting evidence (measurements in the ecliptic plane during the space age; the long-term cosmogenic nuclei [^{14}C and ^{10}Be] record; and *Ulysses* high-latitude solar wind observations) for the size and stability of the floor. Implications of the existence of a floor in the solar wind magnetic field for various topics in solar-heliospheric physics are discussed in § 3.

2. EVIDENCE FOR THE FLOOR

2.1. *Measurements of the Solar Wind in the Ecliptic Plane (1965–Present)*

Figure 1 shows the time series of the 27 day Bartels rotation averages of the solar wind magnetic field magnitude, B, during the space age. Note that for several solar rotations at each solar minimum, the interplanetary magnetic field (IMF) strength reaches a minimum value of ~4.6 nT, the constant in equation (1) obtained for 12 cycles of annual averages of B. A solar rotation period is the shortest interval that can be used to obtain an estimate of a global average of B.

Various lines of evidence support the notion of a floor in the ecliptic plane IMF with magnitude ~4.6 nT as well as the corollary idea that 11 yr sunspot-related variations ride on top of the floor (eq. [1]). First, a separation of the solar wind in the ecliptic at 1 AU into slow solar wind (SSW), high-speed streams (HSSs), and coronal mass ejections (CMEs) (see Table 1 in Richardson et al. 2002) shows that the combined contribution of SSW and HSSs to the average IMF strength was 5.0 nT for the 1972–2000 interval, varying from a mean of 5.5 nT around solar minima to 4.5 nT around solar maxima. During this ~30 yr interval, the CME contribution to the average B was 0.7 nT for epochs of solar minima versus 3.1 nT over solar maxima. Second, Kotov et al. (2002) reported a strong linear relationship between yearly averages of B and the magnitude of the Sun's mean magnetic field (MMF, which is also called the magnetic field of the Sun as a star; the equation and correlation coefficient were updated from Svalgaard et al. 2003):

$$B(\text{nT}) = (0.063 \pm 0.007)\text{MMF}(\mu\text{T}) + (4.87 \pm 0.22)$$
$$(r = 0.84). \quad (2)$$

While the Sun's MMF is often taken to be an indirect measure of the IMF, being essentially proportional to B (Severny et al. 1970; Schatten 1970), the similarity between equations (1) and (2) suggests that the MMF is effectively a measure of the sunspot-related activity solar wind component. Finally, Owens
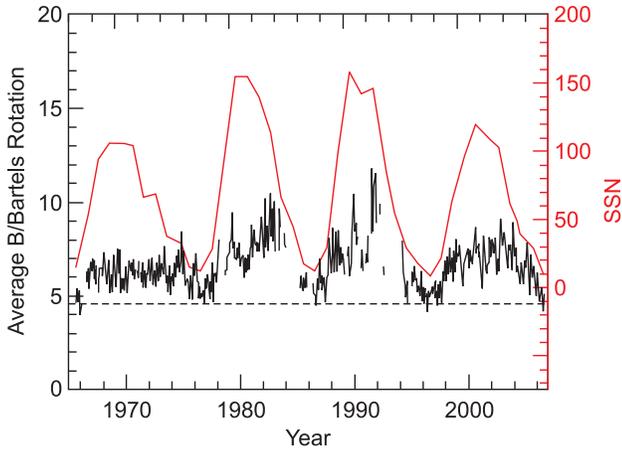
FIG. 1.—Bartels rotation averages of the magnitude of the solar wind magnetic field from 1965 to 2006.

FIG. 2.—Long-term reconstructions of the solar wind magnetic field (B) in the ecliptic plane based on geomagnetic data (IDV), cosmogenic nuclei (^{10}Be and ^{14}C), and sunspot number (SSN). The thin pink line gives annual averages of B deduced from IDV.

& Crooker (2006) have recently simulated the solar cycle variation of the IMF in the ecliptic plane (as shown in Fig. 1) in terms of a constant background open flux with a superposed 11 yr time-varying CME contribution (Webb & Howard 1994).

2.2. Cosmogenic Nuclei (1500–Present)

Figure 2 shows the solar wind magnetic field strength since 1500 as determined from the IDV index (*red curve*, 1856–present; updated from Svalgaard et al. 2005), ^{14}C (*blue curve*, 1500–present Muscheler et al. 2005), ^{10}Be (*green curve*, 1500–present; Caballero-Lopez et al. 2004), and SSN (*purple curve*, 1600–present; Svalgaard et al. 2005). The curves based on cosmogenic nuclei have been scaled to the B-series derived from IDV. Note that both curves for the cosmogenic nuclei have $B \sim 5$ nT for the Maunder minimum (the ~1650–1700 interval circled on the plot; Eddy 1976), for which the SSN was persistently near zero, and thus substantiate equation (1).

Neither the ^{14}C nor the ^{10}Be reconstructions are unique. For example, Caballero-Lopez et al. (2004) present three separate reconstructions of B parameterized by the dependence of the cosmic-ray diffusion coefficient (κ) on B (for the selected curve, $\kappa \sim B^{-3}$), while Solanki et al. (2004, 2005) and Muscheler et al. (2005) obtain conflicting results from analysis of ^{14}C data. Also, other reconstructions/estimates based on sunspot and/or
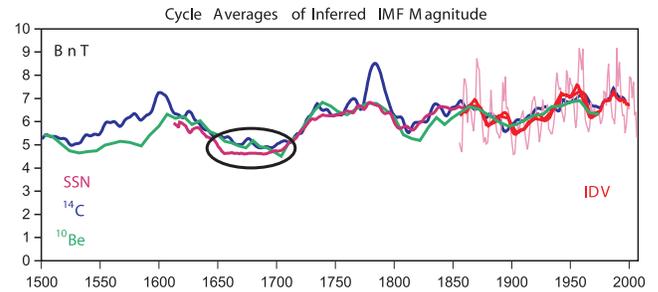
geomagnetic data do not agree with the plotted curves; e.g., Cliver et al. (1998) and Wang & Sheeley (2003) obtained solar wind B-values at Earth of ~1 nT, for the Maunder minimum. If we had no additional evidence to support our claim for the floor, our SSN-based curve in Figure 2 would merely add to the range of possibilities. The existence of such independent evidence (§§ 2.1 and 2.3) argues that equation (1) can be used to constrain the complex models that are used to deconvolve the ^{14}C and ^{10}Be measurements to obtain estimates of the IMF.

2.3. Measurements of the Polar Solar Wind (1993–2006)

Figure 3 shows *Ulysses* out-of-the ecliptic measurements of B during the solar minimum epochs of ~1995 and ~2006. In both cases, *Ulysses* rose above the zone of variable solar wind at a latitude of ~37° and recorded a radial IMF component, scaled to 1 AU by the square of the distance, of ~3.2 nT over the range of polar latitudes (up to ~80°) traversed (Balogh et al. 1995; Smith & Balogh 1995; Forsyth et al. 1996; Smith et al. 2003 [3.30 ± 0.32 nT inbound, 3.03 ± 0.27 outbound]; Balogh & Smith 2006 [3.25 nT, inbound through 2006 November]; for an early suggestion of such latitude independence, see Seuss et al. 1977). While the radial IMF strengths are essentially identical for these two minima, the solar polar magnetic fields are ~40% weaker at present (60 μT vs. 100 μT for ~1995; Svalgaard et al. 2005 and current data from Wilcox Solar Observatory [WSO]). It seems hard to escape the conclusion that the polar fields do not determine the magnitude of the IMF at solar minimum.
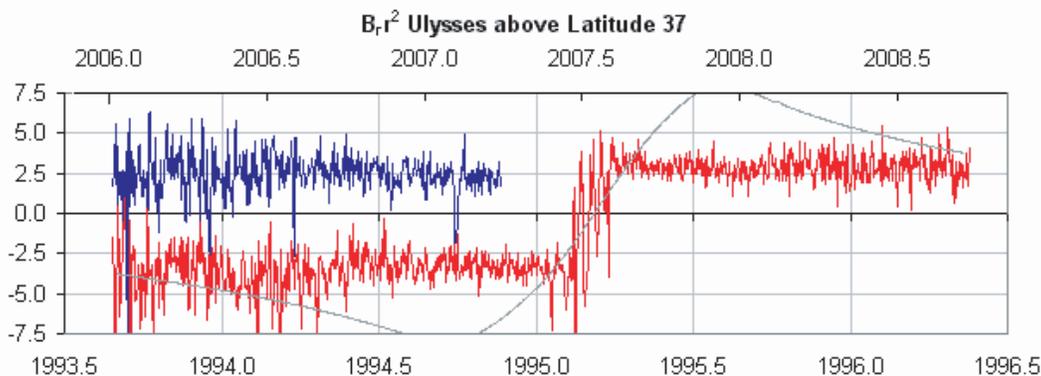

FIG. 3.—*Ulysses* polar pass observations of the radial component of the solar wind magnetic field, adjusted to 1 AU, for the ~1996 and ~2006 solar minimum epochs. The left-hand scale gives hourly averages of the radial field strength in units of nanotesla (*blue and red traces*) and (when multiplied by 10) the heliolatitude of *Ulysses* (*thin gray line*).
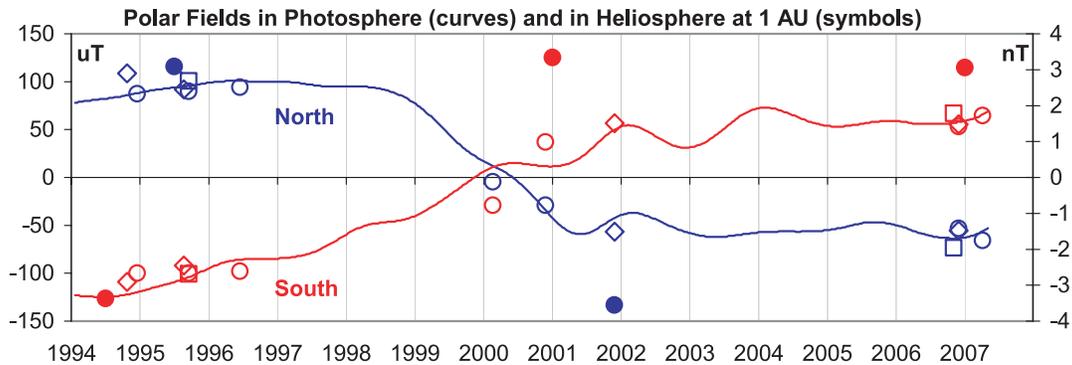
FIG. 4.—*Curves*: WSO polar fields (*left scale*, in units of microtesla) with the annual variation due to the 7.16° tilt of the solar equator from the ecliptic plane suppressed by a 20 nHz filter. *Symbols*: IMF strength, radial component over the poles normalized to 1 AU (*right scale*, in units of nanotesla). *Diamonds*: WSA model with WSO (MWO correction). *Squares*: MHD with WSO (MWO correction). *Open circles*: MAS model with NSO/SOLIS. *Filled circles*: Ulysses $B_r r^2$ (average of all five = 3.27 nT).

2.4. *Connecting the Floor at High and Low Heliolatitudes*

The *Ulysses* observations in Figure 3 provide compelling evidence of "floorlike" behavior in the polar heliosphere, with the radial field independent of latitude and polar field strength. Similarly, Figures 1 and 2 argue for an IMF floor substantially constant on the timescale of centuries in the ecliptic plane. How well do the floors in these different latitude (solar wind) regimes match up? Analysis of 1 minute averages of solar wind data for Bartels rotations with low (<5 nT) average B (to minimize the influence of CMEs) during the 1995–1997 solar minimum indicates a radial component of magnitude ~2.7 nT in the ecliptic plane, comparable to that observed at higher latitudes by *Ulysses*. If we assume an isotropic radial field strength of ~3 nT, we obtain an open solar magnetic flux of ~4 × 10^{14} Wb per hemisphere.

The various studies referred to in § 2.1 lead us to identify the floor in the IMF strength with this inferred baseline open flux of ~4 × 10^{14} Wb, corresponding to a total current of ~10^{11} A in the heliospheric current sheet (HCS; Smith et al. 1978; Duvall et al. 1979). Such constancy of the open flux is a starting point in the recent model of Fisk & Schwadron (2001) for the behavior of the Sun's open magnetic field that is based on a diffusive process resulting from reconnection of open field lines with closed loops.

3. SOME IMPLICATIONS OF A FLOOR IN SOLAR WIND B

3.1. *The Solar Wind during Grand Minima*

Figures 2 and 3 suggest that the IMF strength in the ecliptic plane during grand minima (e.g., Maunder, Spörer) is ~4.6 nT, with a radial field of ~3 nT at all latitudes. Figure 1 suggests that every solar minimum may provide a glimpse into grand minimum solar wind conditions, although the clarity of that glimpse will depend (inversely) on the extent of the overlap between branches of the sunspot butterfly diagram for successive cycles. The solar minimum years with inferred B-values closest to the $R = 0$ value of 4.6 nT in equation (1) were 1901 and 1902 ($B \sim 4.7$ nT) at the depth of the most recent minimum of the ~100 yr Gleissberg cycle (Svalgaard & Cliver 2005). If we are currently approaching another Gleissberg minimum (Svalgaard et al. 2005; Svalgaard & Cliver 2005, 2006), then we may have an opportunity to directly observe such conditions in the coming years. Average B so far for 2007 is already down to 4.6 nT.

3.2. *Solar Wind Models*

The principal competing models that describe the large-scale steady state magnetic field in the inner corona are "source surface" models stemming from the pioneering work of Schatten et al. (1969) and Altschuler & Newkirk (1969) and magnetohydrodynamic (MHD) models following from Mikić et al. (1996) and Usmanov (1996). Both the source surface and MHD models have been developed to the point where they can make specific predictions about the solar wind at 1 AU.

Solar wind models use measurements of the Sun's magnetic field in the photosphere as the inner boundary condition. Although there is debate as to the absolute calibration of the magnetic field measurements, solar observatories agree on the relative strength of the polar fields (Svalgaard et al. 2005). Figure 4 shows time profiles of the line-of-sight solar polar magnetic field strength measured at WSO (*blue and red lines*) from 1994 to 2006, with the annual variation removed. At times where there is a significant axial magnetic dipole, the polar fields dominate over the higher harmonics, and the models predict an IMF that in most of the heliosphere (and especially at high heliographic latitudes) is simply proportional to the open polar cap flux, proxied by the measured polar fields. This is clearly seen in the comparison of the observed solar polar fields and the calculated radial component (*open symbols*) of the polar IMF at 1 AU shown in the figure. Calculations were made both for solar minimum periods in 1995 and 2006 and for rotations when *Ulysses* was at its highest latitudes (north and south) near solar maximum in 2001. For the northern pass near solar maximum in 2001, the polar field was close to zero.

The plotted polar IMF values were obtained from the Wang-Sheeley-Arge (WSA) Potential Field Source Surface model (Arge et al. 2004; N. Arge 2006, private communication) and the "MHD Around a Sphere" (MAS) model (Riley et al. 2001; P. Riley 2007, private communication). When using WSO data as input, both models apply the "saturation" correction specific to and only valid for Mount Wilson Observatory (MWO). For data near the limb, the MWO correction is approximately a factor of 2, close to the correction appropriate for WSO (1.8: Svalgaard et al. 1978; 1.86: Svalgaard 2006). Also plotted are the MHD calculations of IMF strength using National Solar Observatory (NSO)/Synoptic Optical Long-term Investigations of the Sun (SOLIS) data (which do not require correction), giving essentially the same results.

While the calculated polar IMF values in Figure 4 faithfully track the measured photospheric polar fields (see also Fig. 3*a*

in Wang et al. 2006), high-latitude (>40°) *Ulysses* measurements (*filled circles*) reveal a constant radial magnetic field strength of 3.27 ± 0.16 nT (normalized to 1 AU), independent of time, latitude, or the polar field measured in the photosphere, contrary to our own specific prediction (Svalgaard et al. 2005). This is especially puzzling at solar minimum, when the polar fields are the largest scale magnetic structures.

3.3. *Precursor Models for the Next Sunspot Maximum*

The precursor method for predicting the amplitude of the solar cycle (Schatten et al. 1978) is based on the premise that the polar fields of the Sun at minimum, as remnants of the previous cycle, are the "seed field" for the next cycle. Direct observations of polar fields since the 1950s bear this expectation out and show simple, approximate proportionality between polar field strength and the peak (smoothed) SSN for the following cycle (Svalgaard et al. 2005). Before polar fields were directly observed for several solar cycles, however, geomagnetic data were frequently used as a proxy for the polar fields (e.g., Bounar et al. 1997) under the assumption that the IMF strength in the heliosphere at solar minimum mirrored that of the polar field. Figure 4 shows that this assumption is not valid and that prediction based on geomagnetic data (e.g., Hathaway & Wilson 2006) lacks this simple physical basis.

4. CONCLUSION

Various lines of evidence indicate that the solar wind magnetic field has a "floor" or baseline state to which it falls when the sunspot number goes to zero for extended intervals (several rotations). During such periods, the IMF in the ecliptic plane at 1 AU is ~4.6 nT, and the radial component of the polar IMF at 1 AU is ~3 nT, independent of the solar polar field strength. The floor appears to have been stable since ~1500. We identify the floor with a constant solar open magnetic flux of ~4 × 10^{14} Wb and a constant corresponding strength (~10^{11} A) of the current in the HCS. Solar cycle variations of the IMF ride atop the floor.

The existence of a floor in the solar wind has a bearing on such topics as the solar dynamo, space weather, and cosmic-ray modulation. Specific implications of the floor for solar grand minima, solar wind models, and the precursor method for prediction of sunspot maxima were discussed in § 3. The basic question of how the Sun maintains a constant baseline open flux in the face of variable polar field strength remains unanswered. The strength of the solar polar fields does not determine the IMF strength.

REFERENCES

Altschuler, M. D., & Newkirk, G., Jr. 1969, Sol. Phys., 9, 131
Arge, C. N., Luhmann, J. G., Odstrcil, D., Schrijver, C. J., & Li, Y. 2004, J. Atmos. Sol.-Terr. Phys., 66, 1295
Balogh, A., & Smith, E. J. 2006, AGU Fall Meeting, Abstract No. SH44A-05
Balogh, A., Smith, E. J., Tsurutani, B. T., Southwood, D. J., Forsyth, R. J., & Horbury, T. S. 1995, Science, 268, 1007
Bounar, K. H., Cliver, E. W., & Boriakoff, V. 1997, Sol. Phys., 176, 211
Caballero-Lopez, R. A., Moraal, H., McCracken, K. G., & McDonald, F. B. 2004, J. Geophys. Res., 109(A12), A12102
Cliver, E. W., Boriakoff, V., & Bounar, K. H. 1998, Geophys. Res. Lett., 25(6), 897
Duvall, T. L., Jr., Scherrer, P. H., Svalgaard, L., & Wilcox, J. M. 1979, Sol. Phys., 61, 233
Eddy, J. A. 1976, Science, 192, 1189
Fisk, L. A., & Schwadron, N. A. 2001, ApJ, 560, 425
Forsyth, R. J., Balogh, A., Horbury, T. S., Erdös, G., Smith, E. J., & Burton, M. E. 1996, A&A, 316, 287
Hathaway, D. H., & Wilson, R. M. 2006, Geophys. Res. Lett., 33(18), L18101
Kotov, V. A., Kotov, S. V., & Setyaev, V. V. 2002, Sol. Phys., 209, 233
Mikić, Z., Linker, J. A., & Colburn, J. A. 1996, BAAS, 28, 868
Muscheler, R., Joos, F., Müller, S. A., & Snowball, I. 2005, Nature, 436, 3
Owens, M. J., & Crooker, N. U. 2006, J. Geophys. Res., 111, 104
Richardson, I. G., Cane, H. V., & Cliver, E. W. 2002, J. Geophys. Res., 107(A8), SSH 8-1
Riley, P., Linker, J. A., & Mikić, Z. 2001, J. Geophys. Res., 106(A8), 15889
Schatten, K. H. 1970, Sol. Phys., 15, 499
Schatten, K. H., Scherrer, P. H., Svalgaard, L., & Wilcox, J. M. 1978, Geophys. Res. Lett., 5, 411

Schatten, K. H., Wilcox, J. M., & Ness, N. F. 1969, Sol. Phys., 6, 442
Seuss, S. T., Richter, A. K., Winge, C. R., & Nerney, S. F. 1977, ApJ, 217, 296
Severney, A., Wilcox, J. M., Scherrer, P. H., & Colburn, D. S. 1970, Sol. Phys., 15, 3
Smith, E. J., & Balogh, A. 1995, Geophys. Res. Lett., 22(23), 3317
Smith, E. J., Tsurutani, B. T., & Rosenberg, R. L. 1978, J. Geophys. Res., 83, 717
Smith, E. J., et al. 2003, Science, 302, 1165, DOI: 10.1126/science.1086295
Solanki, S. K., Usoskin, I. G., Kromer, B., Schüssler, M., & Beer, J. 2004, Nature, 431, 1084
———. 2005, Nature, 436, 4
Svalgaard, L. 2006, in 2006 SHINE Workshop, July 31–August 4, Midway, Utah
Svalgaard, L., & Cliver, E. W. 2005, J. Geophys. Res., 110(A12), A12103
———. 2006, J. Geophys. Res., 111(A9), A09110
Svalgaard, L., Cliver, E. W., & Kamide, Y. 2005, Geophys. Res. Lett., 32(1), L01104
Svalgaard, L., Cliver, E. W., & LeSager, P. 2003, in Proc. ISCS Symp., Solar Variability as an Input to the Earth's Environment, ed. A. Wilson (ESA SP-535; Noordwijk: ESA), 15
Svalgaard, L., Duvall, T. L., Jr., & Scherrer, P. H. 1978, Sol. Phys., 58, 225
Usmanov, A. V. 1996, in AIP Conf. Proc. 382, Solar Wind Eight, ed. D. Winterhalter (Woodbury: AIP), 141
Wang, Y.-M., & Sheeley, N. R., Jr. 2003, ApJ, 590, 1111
———. 2005, ApJ, 625, 522
Wang, Y.-M., Sheeley, N. R., Jr., & Rouillard, A. P. 2006, ApJ, 644, 638
Webb, D. F., & Howard, R. A. 1994, J. Geophys. Res., 99, 4201