



# The Interplanetary Causes of Magnetic Storms, HILDCAAs and Viscous Interaction

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**Abstract.** A review of the interplanetary causes of geomagnetic activity is presented. Intense southward interplanetary magnetic fields in the sheath region ahead of fast interplanetary manifestations of solar CMEs (ICMEs), and the intrinsically high  $B_z$  fields of magnetic clouds within ICMEs, are the two most predominant causes of major storms with  $D_{ST} \leq -100$  nT. This is true during solar maximum when ICMEs dominate the interplanetary medium and also during the declining phase of the solar cycle when corotating streams and proto-corotating interaction regions (PCIRs) are the dominant large scale structures. PCIRs are high magnetic field regions caused by the interaction of coronal hole high-speed streams with the upstream slow speed streams. PCIRs cause only moderate to weak magnetic storms (rarely storms with  $D_{ST} \leq -100$  nT) because of the highly variable  $B_z$  structure within them. It is thought that the  $B_z$  fluctuations within the PCIR are compressed high-speed stream Alfvén waves. The  $B_z$  fluctuations associated with nonlinear Alfvén waves within the high-speed streams cause continuous auroral activity called HILDCAAs. These HILDCAA events lead to annual AE averages that are sometimes higher during the solar cycle descending phase (such as in 1974) than during solar maximum (1979 or 1981). We quantify an upper limit of the efficiency of viscous interaction energy input into the magnetosphere:  $1$  to  $3 \times 10^{-3}$  of the solar wind ram energy. This is in contrast to an efficiency of  $5$  to  $10 \times 10^{-2}$  for magnetic reconnection during substorms and magnetic storms. Finally, a specific mechanism of viscous interaction is explored: low latitude boundary layer (LLBL) resonant wave-particle interactions. The waves are sufficiently intense to cross-field diffuse magnetosheath plasma onto closed field lines to create the LLBL. Pitch angle scattering will lead to auroral energy deposition of  $\sim 1$  erg  $\text{cm}^{-2} \text{s}^{-1}$ , sufficient for the creation of the dayside

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## 1 Introduction

### 1.1 Empirically Determined Interplanetary Conditions For Major ( $D_{ST} < -100$ nT) Magnetic Storms

The “average” solar wind has a speed of  $\sim 400$  km  $\text{s}^{-1}$  and an embedded magnetic field of  $\sim 5$  nT. For major magnetic storms, the IMF intensity must be substantially higher than this value, and the solar wind speed also higher. The field must also be southwardly directed for a substantial length of time. Gonzalez and Tsurutani (1987) used ISEE-3 field and plasma data to determine an empirical relation for the interplanetary causes of magnetic storms with  $D_{ST} \leq -100$  nT. For the ten events studied, they found that the interplanetary duskward electric fields ( $-V_{SW} \times B$ ) were greater than  $5$  mV/m $^{-1}$  over a period exceeding 3 hours. The electric field condition is approximately equivalent to  $B_z \approx -10$  nT. Although this empirical relationship was determined for a limited data interval during solar maximum, it appears to hold during solar minimum as well (Tsurutani et al., 1995a). To continue to test this relationship, a challenge is issued to find a  $D_{ST} \leq -100$  nT storm without such interplanetary conditions. A bottle of champagne will be given for the first contrary example.

The physical mechanism for solar wind energy transport into the magnetosphere is reasonably well understood. The coupling mechanism is magnetic reconnection between southwardly directed IMF and the northward magnetopause fields (Dungey, 1961). Recent work by Weiss et al. (1992) has indicated that the efficiency of this process during magnetospheric substorms is about 5%. Earlier estimates by Gonzalez et al. (1989) indicated that the efficiency during magnetic storms is 5 to 10%.



Fig. 1. Coronal Mass Ejection (CME) observed in white light on August 18, 1980 (from the High Altitude Observatory/Solar Maximum Mission Archives).

## 2 CMEs, ICMEs, Magnetic Clouds, Driver Gases, and Shocks and Sheaths

During solar maximum, the dominant type of solar “event” related to major geomagnetic activity at Earth are fast ICMEs (Tsurutani *et al.*, 1988a; Gosling *et al.*, 1990). By fast, we mean faster than the upstream slow solar wind so that shocks (and consequently sheaths) are formed. The sheaths consist of shocked accelerated slow solar wind and should not be considered part of the ICME itself.

Figure 1 shows a canonical CME. Starting from the outermost region, it is composed of bright outer loops, a dark region, and closest to the sun, a filament or prominence. These three components form a CME. Figure 2 shows a schematic of a radial profile of a fast ICME and its upstream material. First we consider the ejecta material itself. The ejecta material was originally called a driver gas by Bame *et al.* (1979) because it “drove” the upstream shock. Such material was first identified by Hirshberg *et al.* (1970) by recognizing that clumps of high density  $\text{He}^{++}$  present indicated a significantly different plasma. Occasionally, the driver gas magnetic fields have the form of a “magnetic cloud” or giant flux rope (Burlaga *et al.*, 1981; Klein and Burlaga, 1982).

One fundamental question that should be asked is “what does a magnetic cloud correspond to within the ICME?” Tsurutani and Gonzalez (1997) have speculated that because of the low  $\beta$  nature of a magnetic cloud (see also Farrugia *et al.*, 1997), it most likely corresponds to the dark region of the CME. Previous examples have noted that there is occasionally a layer of highly ionized Fe (and  $\text{He}^{++}$ ) upstream of a magnetic cloud (Galvin *et al.*, 1987). Tsurutani and Gonzalez (1997) have speculated that this corresponds to the bright outer loops of the CME. Additional evidence of the detection of loops in interplanetary space is given in Tsurutani *et al.* (1998a). To the authors’ knowledge, no evidence of the filaments has been found in interplanetary space. Because all of the three CME pieces have not been identified at 1 AU, we call these ICMEs or interplanetary CMEs. They are the

interplanetary manifestations of CMEs, but it is possible they are not exactly the same thing as a CME at the Sun.

The sheath material is shocked slow speed upstream plasma and has different ionic composition than the ejecta material itself. This has been very nicely illustrated by Grande *et al.* (1996). Grande *et al.* (1996) examined a double-main phase magnetic storm (of March 1991) using CRRES ion data. The southward IMFs in the sheath and the trailing magnetic cloud cause the two main phases. They noted that the dominant Fe charge state changed at one point from +9 to +16, which the authors suggest identify the different interplanetary plasma regions (the sheath and the magnetic cloud). It is possible that many of

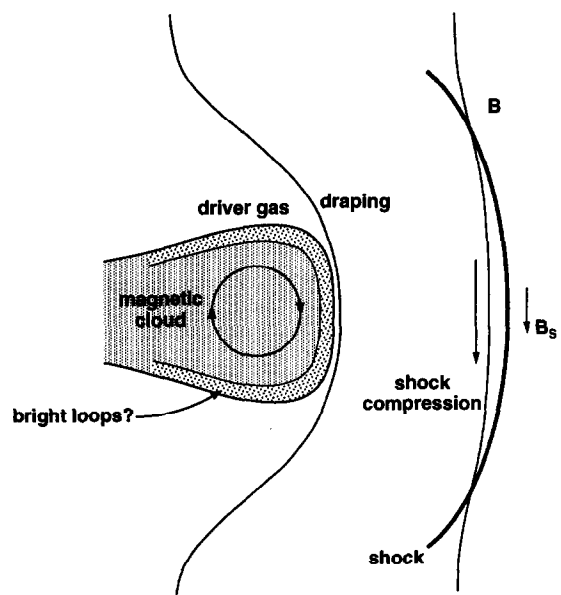


Fig. 2. Schematic figure of an Interplanetary Coronal Mass Ejection (ICME).

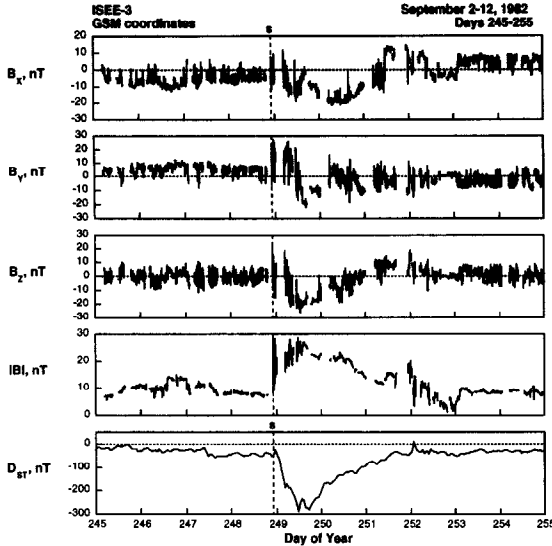


Fig. 3. ISEE-3 magnetic field  $x$ ,  $y$ , and  $z$  components and magnitude (top four panels), and  $D_{ST}$  indices (bottom panel) for September 2-12, 1982.

the largest magnetic storms are actually composed of two smaller events superposed. This has been recently discussed by Kamide *et al.* (1997) and is addressed in more detail in Daglis *et al.* (1998) and Tsurutani *et al.* (1998b).

The two regions of the schematic in Figure 2 where there are large IMFs are the sheath and the driver gas proper. The sheath fields are shock-compressed slow solar wind fields. If the upstream IMF orientation is southwardly directed, this component will be intensified by the field compression. There are many examples of this phenomenon in the literature. The magnetic fields within the ICME are quite intense and can reach magnitudes up to 60 nT (Tsurutani *et al.*, 1992). If the ICME contains a magnetic cloud within it, the intense  $B_s$  will cause an intense magnetic storm. The bright loop fields generally have the same orientation as the adjacent magnetic cloud fields, but are less intense and spatially smaller in extent ( $T \ll 3$  hrs).

Although considerable emphasis has been placed on ICMEs and consequential magnetic storm occurrence, it should be noted that only one out of six events impinging upon the Earth's magnetosphere create a storm with  $D_{ST} < -100$  nT. Tsurutani *et al.* (1988b) have stated that the poor correlation is caused by the orientation of the IMF. The fields are sometimes northward or lie in the ecliptic plane. There also may be intense southward fields, but with only short time durations. Velocity variations seem to play only a small role in geoeffectiveness. Great ( $D_{ST} < -250$  nT) magnetic storms are often caused by relatively moderate speed ICMEs (Tsurutani *et al.*, 1992).

Figure 3 illustrates a case where  $B_s$  fields within the magnetosheath cause a great magnetic storm. Prior to the

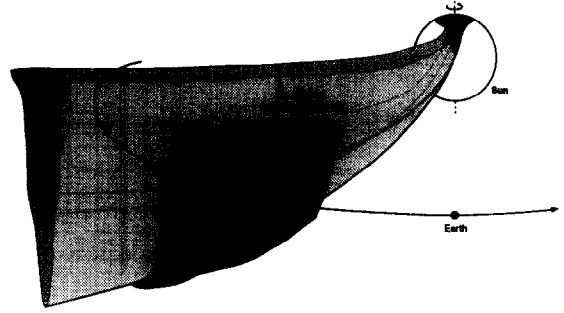


Fig. 4. Corotating Interaction Region (CIR).

shock (denoted by a dashed vertical line) low-level geomagnetic activity is maintained by slightly southward IMF and low-level magnetic reconnection. The fields in the post-shock region double to  $\sim 20$  nT with an amplification of the  $B_s$  component, and lead to the main phase onset.

Although ICMEs are known to be the main causes of magnetic storms during solar maximum, they are also the main source of major magnetic storms during the declining phase as well (Tsurutani *et al.*, 1995a).

### 3 Coronal Holes, Fast Streams, Proto-CIRs

Phillips *et al.* (1995) have shown that fast streams with speeds of 750 to 800 km s<sup>-1</sup> emanate from coronal holes. Their velocities are relatively constant. The high speed streams are also characterized by nonlinear  $\Delta B / B_0 \approx 1 - 2$  Alfvén waves propagating in the antisolar direction (Tsurutani *et al.*, 1994; Smith *et al.*, 1995; Balogh *et al.*, 1995).

When the high-speed streams collide with slower speed streams as shown in Figure 4, a region of compressed magnetic fields is formed. This has been called a Corotating Interaction Region (CIR) because such a structure "corotates" with the solar rotating period. CIRs were discovered in the Pioneer 10 and 11 data at distance from 1.5 to 5 AU (Smith and Wolf, 1976) where the structures were bounded by fast forward and fast reverse shocks. However, it should be noted that at 1 AU, CIRs typically are not bordered by a fast forward shock and have a reverse shock only  $\sim 20\%$  of the time (Tsurutani *et al.*, 1995a). For this reason CIRs at 1 AU have been called Proto-CIRs (PCIRs).

The field strengths of PCIRs have intensities greater than 20 nT and  $B_s$  values are often the same strength. The  $B_z$  component (and other components as well) are highly fluctuating and the intensity of the concomitant magnetic storm is therefore only moderate ( $-100$  nT  $\leq D_{ST} \leq -50$  nT) to weak ( $-50 \leq D_{ST}$ ). One example is shown in Figure 5.

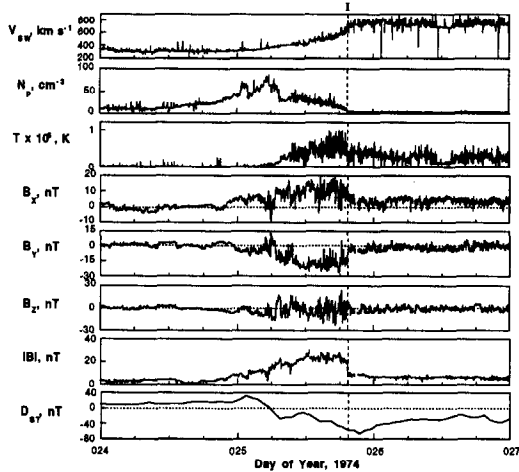


Fig. 5. IMP-8 plasma and magnetic field, and  $D_{ST}$  data for January 24-27, 1974.

The PCIR is composed of compressed and accelerated slow plasma in its leading, antisolarward front, and compressed and decelerated fast solar wind in its trailing solarward portion. These two regions are separated by a stream-stream interface which is usually a tangential discontinuity. Tsurutani *et al.* (1995b) have speculated that the fluctuations on the trailing portion are compressed Alfvén waves which are intrinsic to the high-speed stream

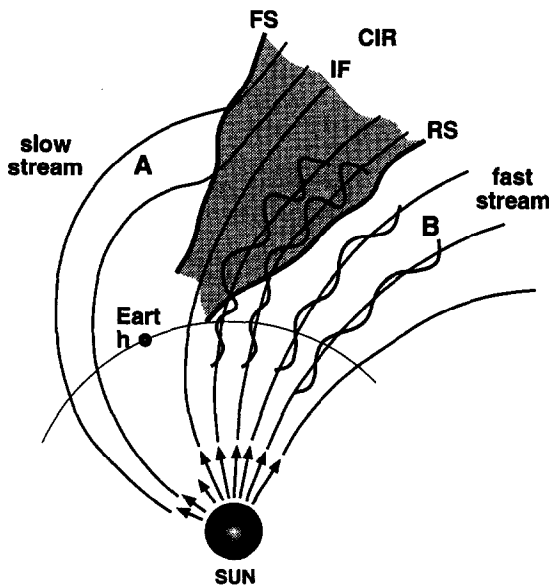


Fig. 6. Schematic of a corotating interaction region (CIR). The CIR (shaded region) is formed by the interaction of a high speed stream (B) with a slow speed stream (A). The forward shock (FS), interface surface (IF), and reverse shock (RS) are indicated.

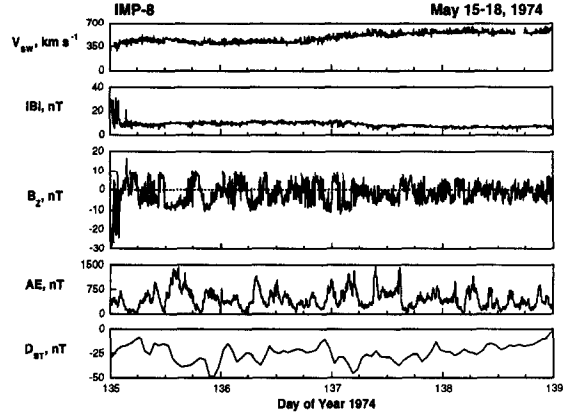


Fig. 7. IMP-8 plasma and magnetic field, AE, and  $D_{ST}$  data for a storm recovery phase (May 15-18, 1974).

proper. Due to space limitation, we only show a schematic figure, Figure 6.

#### 4 Fast Streams, Alfvén Wave Trains and HILDCAAs

It is possible that geomagnetic activity may be higher during solar minimum than solar maximum! Although there are a greater number of ICMEs and intense magnetic storms during solar maximum, these events are episodic in nature. On the other hand, in 1974, during the descending phase, there were two high-speed streams which continuously impinged on the Earth's magnetosphere. The AE average in 1974 was 283 nT in comparison to AE averages of 221 nT in 1979 and 237 in 1981 (dual solar maxima).

The AE activity was primarily in the form of High-Intensity Long-Duration Continuous AE activity (HILDCAAs) (Tsurutani and Gonzalez, 1987). It has been shown that HILDCAAs are caused by the southward components of the Alfvén wave train magnetic fields present in the high-speed streams. A substorm occurs with each southward turning (Figure 7), and because the waves are continuous and large amplitude, the substorms are large and essentially continuous. Also noticeable in the figure are  $D_{ST}$  decreases with each AE increase. The HILDCAAs lead to continuous sporadic influx of particle energy into the outer portions of the magnetosphere. The average  $D_{ST}$  may remain suppressed (in this case at  $\sim -25$  nT) for days or weeks, and appear as an unnaturally long storm recovery phase. However, as Friedel *et al.* (1997) have shown, this low level of negative  $D_{ST}$  is maintained by sporadic (substorm) particle injections, so  $D_{ST}$  appears to not "relax" back to the zero level.

The total annual energy input due to HILDCAAs has not been calculated to date. The annual energy injection associated with magnetic storms during solar maximum would be an interesting number for comparison. If  $D_{ST}$  and

$dD_{ST}/dt$  are to be used to make these estimates (Dessler and Parker, 1959; Skopke, 1966; Gonzalez *et al.*, 1994), the difficulty is in determining the lifetimes  $\tau$  of the ring current and  $L = 5$  to 7 substorm particles. This depends on the ion species, energy pitch angle and position of the ring-current, and is therefore a complex problem (Gonzalez *et al.*, 1994). However, if one makes an estimate that  $\tau \sim 1$  hour for substorm particles and  $\tau \sim 10$  hours for storm ring-current particles, then the integrated effect of all substorms during HILDCAAs dominates the total energy picture. Thus, order of magnitude calculations indicate that there was more total energy input into the magnetosphere during 1974 than in 1979 (solar maximum). However, a more exact calculation should be done in the future.

### 5 Upper Limit on the Efficiency of Viscous Interaction

Although it is thought that magnetic reconnection and solar wind energy transfer to the magnetosphere occurs for all IMF orientations, it is the least effective during northward fields. For this orientation reconnection would only occur at the cusp region and energy into the magnetosphere proper would be minimum.

One way of estimating the efficiency of viscous interaction (Axford and Hines, 1961), is to examine the energy flow into the magnetosphere during unique interplanetary intervals, such as those with large, long-duration IMF  $B_N$  events. The energy input into the magnetosphere can be approximated by a relation given by Akasofu (1981) which considers the energy input into the ring current, into auroral particles and into Joule heating. Akasofu has derived expressions for proxies involving the  $D_{ST}$ ,  $dD_{ST}/dt$  and AE parameters/indices for all of the three terms.

To calculate the energy efficiency, one must estimate the size of the magnetosphere, use the measured upstream solar wind measurements to determine the ram flux impinging upon the magnetosphere, and then simply divide the two terms. Tsurutani and Gonzalez (1995a) have determined that the efficiency is 1 to  $4 \times 10^{-3}$ .

### 6 PCBL Waves, LLBL waves, Crossfield Diffusion: Viscous Interaction

Recent Polar Plasma Wave Investigation (PWI) results have indicated that intense broadband electric and magnetic waves are detected on dayside magnetic field lines that map into the LLBL regions (Tsurutani *et al.*, 1998c). The waves are detected near Polar apogee at 7 to 8  $R_E$  and near perigee at  $r \sim 2 R_E$ . The waves are present essentially all of the time from 0500 to 1800 LT. The intensities are similar: 1) near Polar perigee, 2) near Polar apogee and 3) at the LLBL. Figure 8 is a schematic showing the regions of wave detection. It is most probable that the waves are present all along the boundary layer field lines. A current driven instability generation mechanism has been proposed

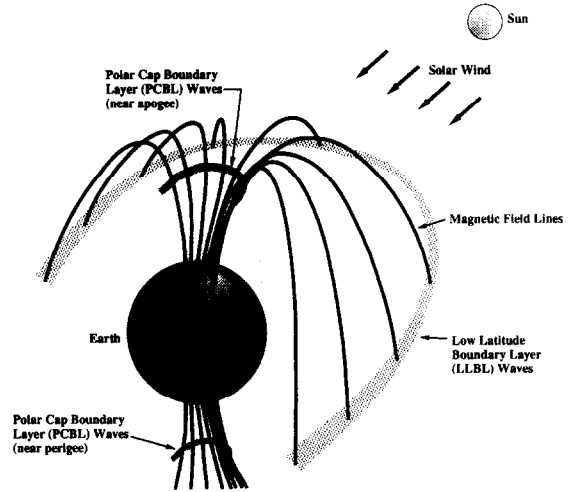


Fig. 8. Schematic figure of Earth's magnetic fields lines mapping through regions of wave detection at low (LLBL) and high (PCBL) latitudes.

(Drake *et al.*, 1994a,b; Drake, 1996) and the model is currently being extended to include density gradients (Lakhina *et al.*, 1997). Such broadband LLBL plasma waves at the magnetopause could lead to cross-field diffusion of magnetosheath plasma.

Tsurutani and Thorne (1982) and Thorne and Tsurutani (1991) have derived expressions for the cross field diffusion of plasma based on resonant wave-particle interactions. They are:

$$D_{\perp} B_w \approx 2 \left( \frac{B_w}{B_0} \right)^2 D_{\max} \quad (1)$$

$$D_{\perp} E_w \approx 2 \left( \frac{c}{v} \right)^2 \left( \frac{E_w}{B_0} \right)^2 D_{\max} \quad (2)$$

where  $B_w$  and  $E_w$  correspond to the magnetic and electric amplitudes of the resonant waves,  $B_0$ ,  $c$ , and  $v$  correspond to the ambient magnetic field, speed of light, and particle speed. The term  $D_{\max}$  is the Bohm diffusion rate given by:

$$D_{\max} = E_{\perp} c / 2eB_0 \quad (3)$$

where  $E_{\perp}$  is the particle perpendicular energy and  $e$  is the particle charge. Using typical wave intensities, plasma densities and magnetic field strengths at the LLBL, Tsurutani and Thorne (1982) illustrated that the plasma would diffuse at  $\sim 0.1 D_{\max}$  which is sufficient to form the LLBL itself. The broadband waves have sufficient intensity to put protons and electrons on near-strong to strong pitch angle diffusion to create the diffuse aurora with energy fluxes of  $\sim 1 \text{ erg cm}^{-2} \text{ s}^{-1}$ .

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## References

- Akasofu, S.I., Energy coupling between the solar wind and the magnetosphere, *Space Sci. Rev.*, **28**, 121, 1981.
- Axford, W.I. and Hines, C.O., A unifying theory of high latitude geophysical phenomena and geomagnetic storms, *Can. J. Phys.*, **39**, 1433, 1961.
- Balogh, A., Smith, E.J., Tsurutani, B.T., Southwood, D.J., Forsyth, R.J., and Hornberg, T.S., The heliospheric magnetic field over the south polar region of the sun, *Science*, **268**, 1007, 1995.
- Bame, S.J., Asbridge, J.R., Feldman, W.C., Fenimore, E.E., and Gosling, J.T., Solar wind heavy ions from flare-heated coronal plasma, *Solar Phys.*, **62**, 179, 1979.
- Burlaga, L.F., Sittler, E., Mariani, F., and Schwenn, R., Magnetic loop behind an interplanetary shock: Voyager, Helios and IMP-8 observations, *J. Geophys. Res.*, **86**, 6673, 1981.
- Daglis, I.A., The role of magnetosphere-ionosphere coupling in magnetic storm dynamics, in *Magnetic Storms*, edited by B.T. Tsurutani, W.D. Gonzalez, Y. Kamide, and J.K. Arballo, Amer. Geophys. Union Press, Washington, D.C., **98**, 107, 1997.
- Daglis, I.A., Summary discussion of solar terrestrial coupling processes, *Phys. Chem. Earth*, this issue, 1998.
- Drake, J.F., Gerber, J., and Kleva, R.G., Turbulence and transport in the magnetopause current layer, *J. Geophys. Res.*, **99**, 1121, 1994a.
- Drake, J.F., Kleva, R.G. and Mandt, M.E., Structure of thin current layers: Implications for magnetic reconnection, *Phys. Rev. Lett.*, **73**, 1251, 1994b.
- Drake, J.F., Magnetic reconnection, a kinetic treatment, in *Physics of the Magnetopause*, Geophys., Mon. **90**, Amer. Geophys. Union, Washington, D.C., 155, 1995.
- Dungey, J.W., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, **6**, 47, 1961a.
- Farrugia, C.J., Burlaga, L.F., and Lepping, R.P., Magnetic clouds and the quiet-storm effect at earth, in *Magnetic Storms*, edited by B.T. Tsurutani, W.D. Gonzalez, Y. Kamide, and J.K. Arballo, Amer. Geophys. Union, Washington, D.C., **98**, 91, 1997.
- Friedel, R.H.W., Korth, A., Mouikis, C., Blake, B., and Scudder, J., A survey of the radiation belt dynamics for the first year of POLAR operations from CEPPAD and HYDRA data, *Proc. Inter. Symp. on Sol.-Terr. Coupling Processes*, 1997.
- Galvin, A.B., Ipavich, F.M., Gloeckler, G., Hovestadt, D., Bame, S.J., Klecker, B., Scholer, M., and Tsurutani, B.T., Solar wind ion charge status preceding a driver plasma, *J. Geophys. Res.*, **92**, 12069, 1987.
- Gonzalez, W.D. and Tsurutani, B.T., Criteria of interplanetary parameters causing intense magnetic storms ( $D_{ST} < -100$  nT), *Planet. Space Sci.*, **35**, 1101, 1987.
- Gonzalez, W.D., Tsurutani, B.T., Gonzalez, A.L.C., Smith, E.J., Tang, F., and Akasofu, S.-I., Solar-wind-magnetosphere coupling during intense magnetic storms (1978-1979), *J. Geophys. Res.*, **94**, 8835, 1989.
- Gosling, J.T., Bame, S.J., McComas, D.J., and Phillips, J.L., Coronal mass ejections and large geomagnetic storms, *Geophys. Res. Lett.*, **127**, 901, 1990.
- Grande, M., Perry, C.H., Blake, J.B., Chen, M.W., Fennell, J.F., and Wilken, B., Observations of iron, silicon and other heavy ions in the geostationary altitude region during late March 1991, *J. Geophys. Res.*, **101**, 24707, 1996.
- Hirshberg, J., Alksne, A., Colburn, D.S., Bame, S.J., and Hundhausen, A.J., Observation of a solar flare induced interplanetary shock and helium-enriched driver gas, *J. Geophys. Res.*, **75**, 1, 1970.
- Howard, R.A., Coronal mass ejections and interplanetary effects, *Phys. Chem. Earth*, this issue, 1997.
- Kamide, Y., Yokoyama, N., Gonzalez, W., Tsurutani, B.T., Brekke, A., and Masuda, S., Two-step development of geomagnetic storms, submitted to *J. Geophys. Res.*, 1997.
- Klein, L.W. and Burlaga, L.F., Interplanetary magnetic clouds at 1 AU, *J. Geophys. Res.*, **87**, 613, 1982.
- Lakhina, G.S., Tsurutani, B.T., Arballo, J.K., Ho, C.M., and Boonsiriset, A., Generation of broadband plasma waves in the polar cap boundary layer, *EOS*, **S297**, 1997.
- Phillips, J.L., Bame, S.J., Feldman, W.C., Goldstein, B.E., Gosling, J.T., Hammond, C.M., McComas, D.J., Neugebauer, M., Scime, E.E., and Suess, S.T., Ulysses solar wind plasma observations at high southerly latitudes, *Science*, **268**, 1030, 1995.
- Smith, E.J. and Wolf, J.H., Observations of interaction regions and corotating shocks between one and five AU: Pioneers 10 and 11, *Geophys. Res. Lett.*, **3**, 137, 1976.
- Smith, E.J., Balogh, A., Neugebauer, M., and McComas, D., Ulysses observations of Alfvén waves in the southern and northern solar hemisphere, *Geophys. Res. Lett.*, **22**, 3381, 1995.
- Thorne, R.M. and Tsurutani, B.T., Wave-particle interactions at the magnetopause boundary layer, in *Physics of Space Plasmas* (1990), ed. by T. Chang et al., Sci. Publ. Inc., Cambridge, Mass., **10**, 119, 1991.
- Tsurutani, B.T. and Thorne, R.M., Diffusion processes in the magnetopause boundary layer, *Geophys. Res. Lett.*, **9**, 1247, 1982.
- Tsurutani, B.T. and Gonzalez, W.D., The cause of high intensity long-duration continuous AE activity (HILDCAAs): Interplanetary Alfvén wave trains, *Planet. Space Sci.*, **35**, 405, 1987.
- Tsurutani, B.T., Gonzalez, W.D., Tang, F., Akasofu, S.-I., and Smith, E.J., Origin of interplanetary southward magnetic fields responsible for major magnetic storms near solar maximum (1978-1979), *J. Geophys. Res.*, **93**, 8519, 1988a.
- Tsurutani, B.T., Goldstein, B.E., Gonzalez, W.D., and Tang, F., Comment on "A new method of forecasting geomagnetic activity and proton showers," by A. Hewish and P.J. Duffett-Smith, *Planet. Space Sci.*, **36**, 205, 1988b.
- Tsurutani, B.T., Gonzalez, W.D., Tang, F., and Lee, Y.T., Great magnetic storms, *Geophys. Res. Lett.*, **19**, 73, 1992.
- Tsurutani, B.T., Ho, C.M., Smith, E.J., Neugebauer, M., Goldstein, B.E., Mok, J.S., Arballo, J.K., Balogh, A., Southwood, D.J., and Feldman, W.C., The relationship between interplanetary discontinuities and Alfvén waves: Ulysses observations, *Geophys. Res. Lett.*, **21**, 2267, 1994.
- Tsurutani, B.T., Gonzalez, W.D., Gonzalez, A.L.C., Tang, F., Arballo, J.K., and Okada, M., Interplanetary origins of geomagnetic activity in the declining phase of the solar cycle, *J. Geophys. Res.*, **100**, 21717, 1995a.
- Tsurutani, B.T., Ho, C.M., Arballo, J.K., Goldstein, B.E., and Balogh, A., Large amplitude IMF fluctuations in corotating interaction regions: Ulysses at midlatitudes, *Geophys. Res. Lett.*, **22**, 3397, 1995b.
- Tsurutani, B.T. and Gonzalez, W.D., The efficiency of "viscous interaction" between the solar wind and the magnetosphere during intense northward IMF events, *Geophys. Res. Lett.*, **22**, 663, 1995.
- Tsurutani, B.T. and Gonzalez, W.D., The interplanetary causes of magnetic storms: A review, in *Magnetic Storms*, edited by B.T. Tsurutani, W.D. Gonzalez, Y. Kamide, and J.K. Arballo, Amer. Geophys. Union Press, Wash. D.C., **98**, 77, 1997.
- Tsurutani, B.T., Ajello, J.M., Arballo, J.K., Lakhina, G.S., Ho, C.M., Sakurai, R., Buti, B., Pickett, J.S., Gurnett, D.L., Lepping, R.P., Peterson, W.K., Rostoker, G. and Kamide, Y., The January 10, 1997 first substorm, submitted to *Geophys. Res. Lett.*, 1998a.
- Tsurutani, B.T., Arballo, J.K., Kamide, Y., Gonzalez, W.D., and Lepping, R.P., Interplanetary causes of great and superintense magnetic storms, *Phys. Chem. Earth*, this issue, 1998b.

Tsurutani, B.T., Ho, C.M., Lakhina, G.S., Boonsiriseth, A., Arballo, J.K.,  
Pickett, J.S., Gurnett, D.A., Peterson, W.K., and Thorne, R.M.,  
Broadband plasma waves observed in the polar cap boundary layer

(PCBL): POLAR, to appear in *J. Geophys. Res.*, 1998c.

Weiss, L.A., Reiff, P.H., Moses, J.J., and Moore, B.D., Energy dissipation  
in substorms, Eur. Space Agency Spec. Publ., *ESA-SP-335*, 309, 1992.