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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 198 1). We quantify an upper limit of the efficiency of viscous interaction energy input into the magnetosphere: 1 to 3 x 10-3 of the solar wind ram energy. This is in contrast to an efficiency of 5 to 10 x 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 tbc LLBL. Pitch angle scattering will lead to auroral energy deposition of ~1 erg $cm^{-2} s^{-1}$, sufficient for the creation of the dayside aurora.

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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 -400 km s^{-1} and an embedded magnetic field of -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 ($-V_{SW}$ x 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%.

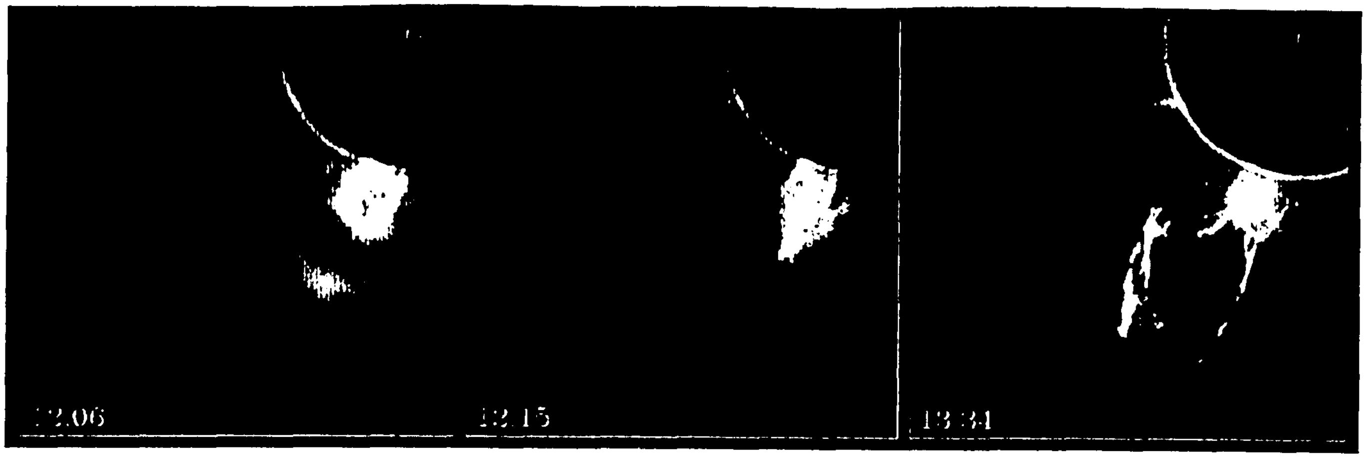


Fig. 1. Coronal Mass Ejection (CME) observed in white light on August 18, 1980 (from the High Altitude Observatory/Solar Maximum Mission Archives).

1.2 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 ejects material itself. The ejects 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 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 β 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 He^{++}) upstream of a magnetic cloud (Galvin et al., 1987), Tsurutani and Gonzalez (1997) have speculated that [his corresponds to the bright outer loops of the CME. No evidence of the filaments have been found in interplanetary space. Because all of the three CME pieces have not been identified at I 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 ejects material itself. This has been very nicely illustrated by Grande et al. (1 996). 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 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

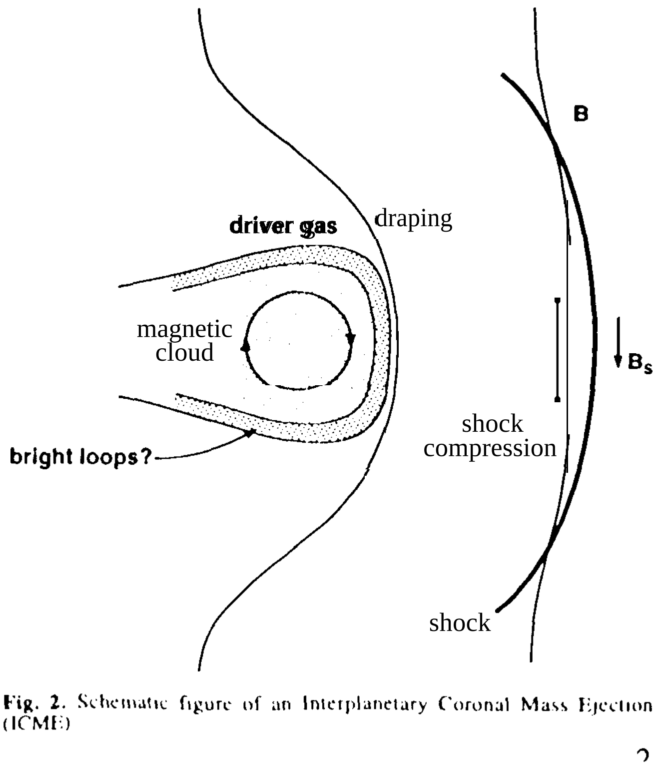


Fig. 2. Schematic figure of an Interplanetary Coronal Mass Ejection (ICME)

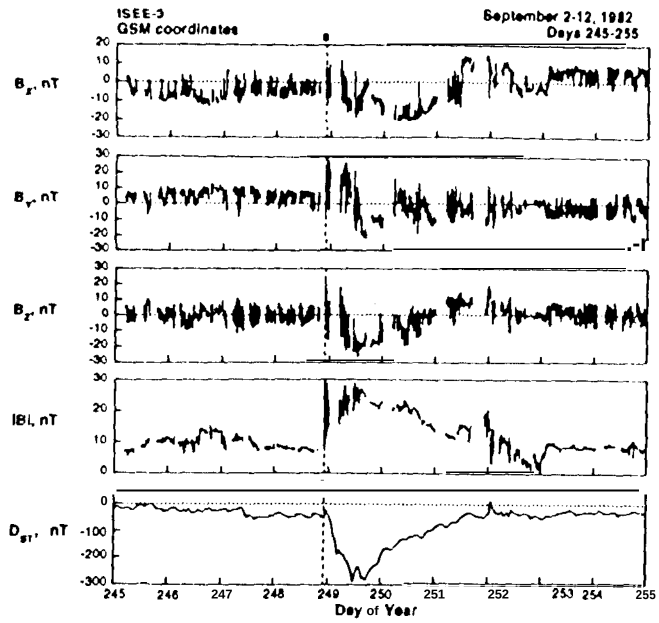


Fig. 3. ISEE-3 magnetic field x, y, and z components and magnitude (top four panels), and D_{ST} indices (bottom panel) for September 2-12, 1982.

detail in Daglis et al. (1997).

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 << 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 secm to play only a small role in geoeffectiveness. Great ($D_{ST} < -250$ nT) magnetic storms arc 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 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

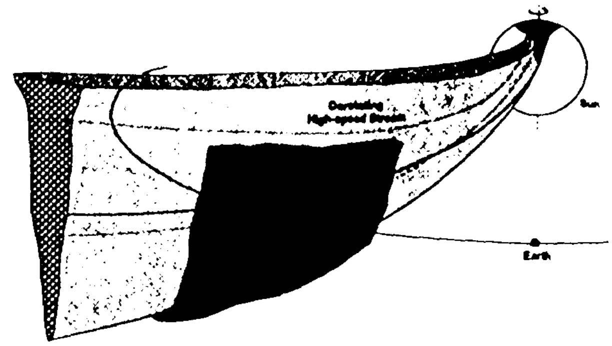


Fig. 4. Corotating Interaction Region (CIR).

the post-shock region double to -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).

1.3 Coronal Holes, Fast Streams, Proto-CIRs

Phillips et al. (1995) have shown that fast streams with speeds of 750 to 800 km s^{-1} 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 -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 (-SO $\leq D_{ST}$). One example is shown in Figure 5,

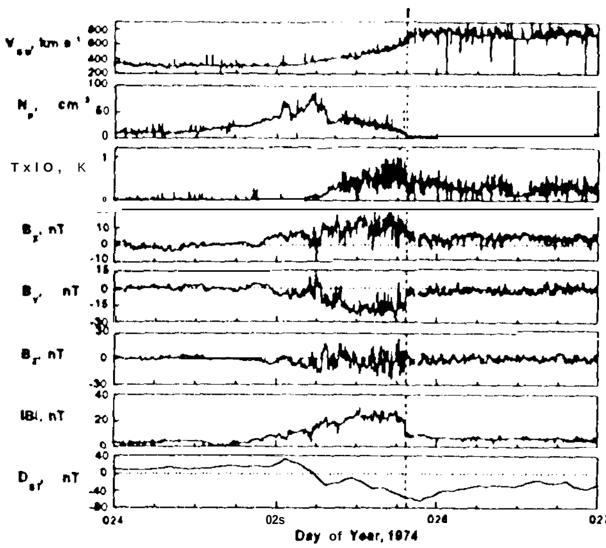
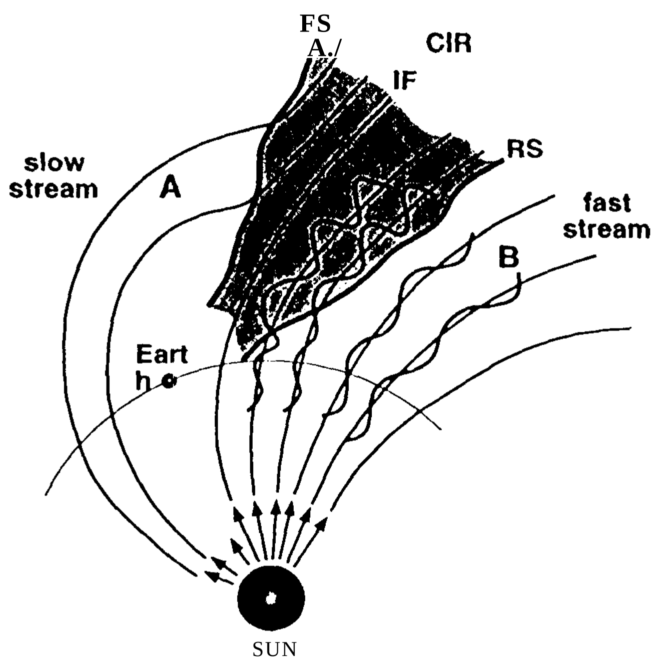


Fig. 5. IMP-8 plasma and magnetic field, and D_{ST} data for January 24-27, 1974.

The PCIR is composed of compressed and accelerated slow plasma in it's 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) has 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 try the interaction of a high speed stream (B) with a slow speed stream (A) The forward shock (FS), interface surface (IF), nnd reverse shock (RS) are indicated

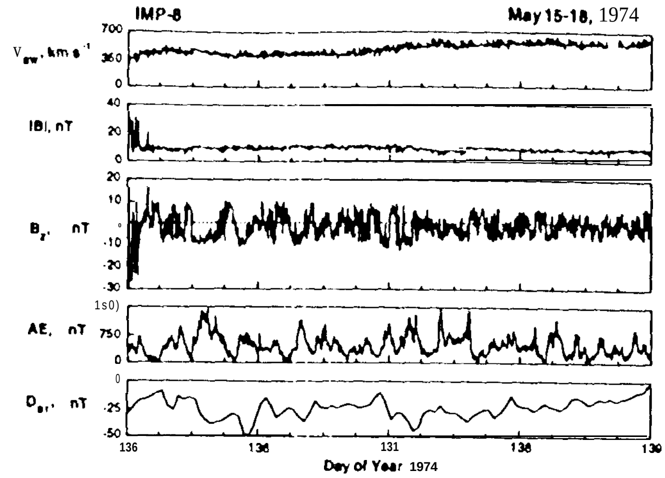


Fig. 7. IMP-8 plasma and magnetic field, AE, and D_{ST} data for a storm recovery phase (May 15-18, 1974),

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

1.4 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 noticable 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 - –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 [o not "relax" back to the zero level,

The total annual energy input due to HILDCAAs has no[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; Sckopke, 1966; Gonzalez et al., 1994), the difficulty is in determining the lifetimes τ 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 τ -1 hour for substorm particles and τ -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.

1.5 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 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 x 10^{-3}.

1.6 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., 1998). The waves are detected near Polar apogee at 7 to 8 R_e and near perigee at r - 2 R_e. The waves are present essentially all of the time from 0500 to 1800 LT. The intensities arc 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 arc present all along the boundary layer field lines. A current driven instability generation mechanism has been proposed (Drake et al., 1994a,b; Drake, 1996) and the model is

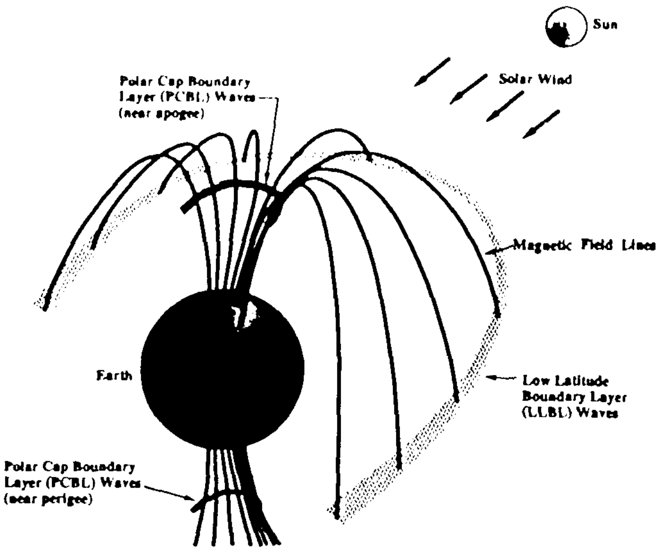


Fig. 8. Schematic figure of Earth's magnetic fields lines mapping through regions of wave detection at low (LLBL) and high (PCBL) latitudes.

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:

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

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

where B_W and E_W correspond to the magnetic and electric amplitudes of the resonant waves, B_o, 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:

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

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 -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 [o create [he diffuse aurora with energy fluxes of ~1 erg cm^{-2} s-t.

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