THE LOW-LATITUDE BOUNDARY LAYER AT THE FLANKS OF THE MAGNETOPAUSE

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Abstract. This is a brief overview on what we know and do not know about the low-latitude boundary layer (LLBL) at the flanks of the magnetotail. On the basis of recent observations, simulations and theories we conclude that reconnection is the dominant process in generating the LLBL and its structure probably even under northward IMF conditions. Part of the LLBL always seems to be on open field lines. Possibly the LLBL possesses a double structure with its outer part open and inner part closed. Anomalous diffusive processes cannot sustain the LLBL but provide sufficient diffusivity for reconnection. Strong diffusion is only expected in narrow localized regions and can make the transition to superdiffusion. Kelvin-Helmholtz instability (KHI) is favoured for northward IMF, producing vortices at the tail flanks. Its contribution to efficient mass transport still remains questionable. Coupling of the LLBL to the ionosphere can strongly affect the internal structure of the LLBL, causing turbulent eddies and detachments of plasma blobs as also field-aligned currents and electron heating. The structure and dynamics of the LLBL are affected by field-aligned electric potentials that decouple the LLBL from the ionosphere. Non-ideal coupling simulations suggest that the dusk flank is decoupled, favouring KHI, while the dawn flank is dominated by currents and turbulence.

Key words: Magnetopause – Boundary Layer – Reconnection – Kelvin-Helmholtz-Instability – Diffusion

1. Introduction

Spacecraft observations have revealed the existence of a layer located just inside the magnetospheric boundary at low geomagnetic latitudes, the low-latitude boundary layer (LLBL), which consists of tailward flowing plasma having properties intermediate between those of the magnetosheath and the magnetosphere. It was first observed by Hones et al. (1972) and Akasofu et al. (1973) along the flanks of the geomagnetic tail, but has also since been shown to be intermittently present at almost all local times along the entire dayside portion of the magnetopause. This boundary layer is supposedly important for the transport of magnetosheath mass, momentum, and energy into the magnetosphere.

There is abundant evidence that the LLBL is at times on open field lines, i.e., magnetospheric field lines having one foot in the ionosphere and extending into the magnetosheath. Its formation on open field lines during southward interplanetary magnetic field (IMF) is well understood in terms of dayside reconnection. There is more circumstantial evidence that the LLBL also exists on closed field lines over some portion of the magnetospheric boundary. The thickness of the LLBL increases with increasing distance from the subsolar point (Haerendel et al., 1978)

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and when the IMF is northward (Haerendel et al., 1978; Mitchell et al., 1987). The anti-sunward component of the flow velocity also increases with distance from the subsolar point (Eastman, 1979). While at the flanks of the magnetopause the LLBL exhibits a density gradient normal to the magnetopause, the LLBL at the dayside magnetopause shows a density plateau, and the LLBL is one of several sublayers of the boundary layer (Paschmann et al., 1990; Song et al., 1994).

Several mechanisms have been discussed in the literature as candidates for the formation of the LLBL. These mechanisms can be divided into magnetic reconnection between the magnetospheric and the magnetosheath magnetic fields, impulsive penetration of magnetosheath plasma, and viscous/diffusive mixing at the magnetopause. While impulsive penetration is only expected to be of importance at the dayside magnetopause, the other two mechanisms can also act along the flanks of the magnetopause. Since this review is primarily concerned with the LLBL at the flanks, we will not discuss impulsive penetration, but will review work done on the other two processes and their implications for the LLBL at the flanks of the magnetopause. Recent reviews on this topic can also be found in Lotko and Sonnerup (1995), Miura (1995b), Treumann et al. (1995), and Winske et al. (1995).

2. Reconnection Under Northward Interplanetary Magnetic Field

Nishida (1989) has proposed that when the interplanetary magnetic field (IMF) is northward transient and localized reconnection may occur on the dayside magnetopause and may lead to the formation of the LLBL. Figure 2 schematically illustrates the resulting magnetic field configuration. The reconnection regions are indicated by large dots. In this model the momentum in the solar wind in the magnetosheath is transported into the LLBL directly with the entering plasma and indirectly as the reconnected field lines are pulled by the solar wind plasma. Only those geomagnetic field lines will contain magnetosheath plasma that have been open at some time in the past. Thus, according to this model, the LLBL is an entity of flux tubes which have well-defined boundaries. The blobs observed by Sckopke et al. (1981) are taken as evidence for such well-defined flux tubes.

Magnetic reconnection at high latitudes behind the polar cusps has been proposed by Song and Russell (1992) as a process for the formation of the LLBL. The process is schematically shown in Figure 2 and follows the suggestion of Dungey (1961) for reconnection under northward IMF. A magnetosheath flux tube (thick line), which drapes over the stagnation point, moves relatively slowly with respect to the magnetospheric fields and is likely to reconnect at high latitudes, where the magnetosheath and the lobe field are antiparallel. After reconnection the poleward portion of the flux tube convects tailward with the solar wind flow. In the dayside portion of the flux tube the magnetospheric and the magnetosheath plasmas mix and the flux tube sinks into the magnetosphere. During this process the flux tube length shortens and the diameter decreases, assuming that the flux tube field is the

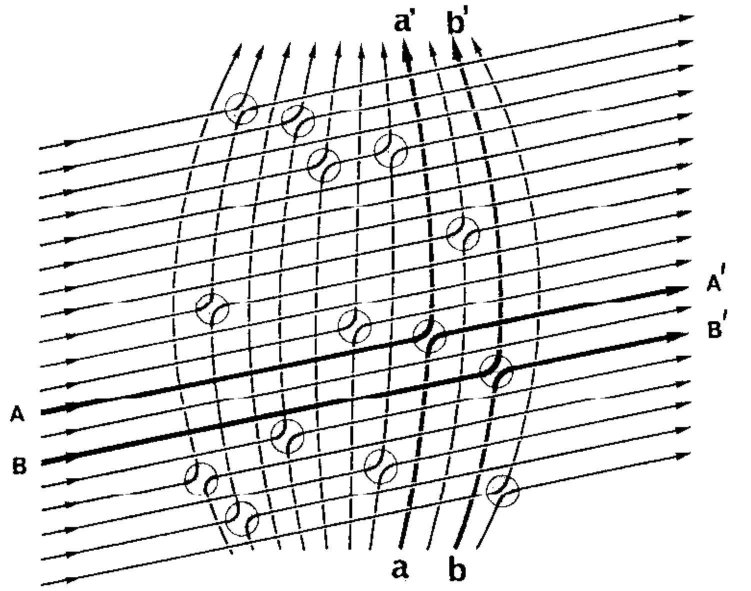

Figure 1. Schematic illustration of the field line configuration at the dayside magnetopause when random reconnection occurs between the interplanetary magnetic field and the geomagnetic field (from Nishida, 1989).

same as the magnetospheric field when it enters the magnetosphere. If the magnetospheric flux tube is initially open, little or no magnetospheric plasma will be found on this flux tube and after rearrangement the density in the flux tube will decrease. The decrease in volume leads to a temperature increase. This flux tube will have a higher pressure than other adjacent magnetospheric flux tubes. Song and Russell (1992) have argued that, due to the requirement for the interchange instability, the newly added flux tube will subsequently only expand azimuthally rather than radially. Radial interchange would lead to a pressure increase and is therefore stable, while azimuthal interchange proceeds spontaneously. The boundary layer would disperse along the magnetopause indefinitely, since in the expansion process thermal energy is converted into kinetic energy and the boundary layer flow is accelerated. Song et al. (1994) have taken into account the drag force of the ionosphere due to field-aligned currents. The motion of the boundary layer drives field-aligned currents that close in the ionosphere; the resulting drag force may eventually stop the boundary layer flow or may balance the driving pressure force, so that the flow moves with constant speed.

Fuselier et al. (1995) have presented evidence that reconnection does not necessarily occur simultaneously as proposed in the qualitative Song and Russell (1992) picture. They identified a magnetosheath boundary layer (MSBL) near the dayside

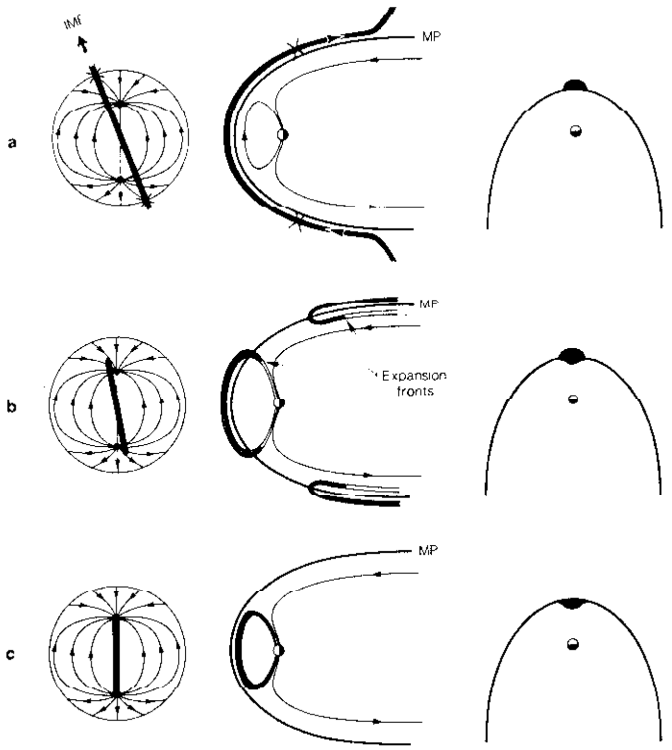

Figure 2. Model for the formation of the low-latitude boundary layer through merging behind the polar cusp with northward IMF. The three views are from the sun, from dusk, and from above the ecliptic plane (after Song and Russell, 1992).

magnetopause at the magnetosheath side of the magnetopause current layer and the LLBL. This MSBL is characterized by unidirectional streaming electrons: one half of the distribution parallel to the magnetic field has the characteristics of the distribution in the nearby magnetosheath (actually in the plasma depletion layer), the other half is similar to the distribution in the LLBL on the Earthward side of the current layer. The existence of such an MSBL suggests that reconnection does not occur simultaneously at both high latitude reconnection sites. Reconnection may be limited to one hemisphere, as sketched in Cowley's (1983) catalog of magnetospheric topology for northward IMF. Reconnection between the IMF and open tail field will convert open tail lobe field lines into open field lines that drape over the dayside magnetopause. These field lines are then carried by the solar wind downstream and can constitute a layer of open field lines earthward of the magnetopause (Crooker, 1992).

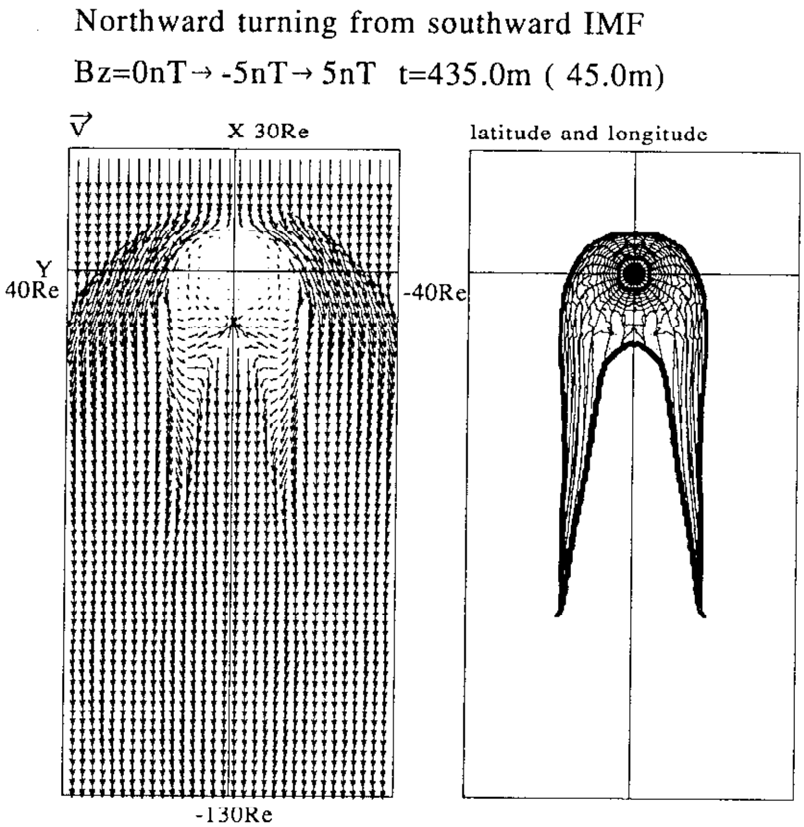

Figure 3. Results from a global MHD simulation (45 min after northward IMF turning). (Left) Flow vectors in the equatorial plane. (Right) Latitude and longitude mapping of magnetic field lines from the ionosphere to their crossing point of the equatorial plane in the tail (from Ogino et al., 1994).

The process of high latitude reconnection and magnetospheric incorporation of newly closed flux tubes should be a persistent feature of global magnetospheric simulations. A number of different groups have performed global MHD simulations of the magnetosphere under northward IMF and we will now present results pertinent to the boundary layer problem. Usadi et al. (1993) presented global simulations for northward IMF wherein reconnection occurs at high latitudes behind the cusps. The magnetic flux from the outer surface of the magnetotail lobes was peeled away like the skin of an onion. The resulting decrease of the magnetic pressure in the lobe led to a dipolelike structure and the magnetotail attained the structure of a tadpole. However, probably because of the limited simulation region, the newly closed flux tubes accumulated at the dayside, so that this simulation effort did not result in a boundary layer. Similar results have been obtained by Fedder and Lyon (1995). They investigated the asymptotic magnetospheric state after a few hours of steady northward IMF. In this case no open tail lobes were present and no Earth-connected flux was seen tailward of 155 R_E. The simulations resulted in a boundary layer which was mechanically driven: the expansion of the magnetosheath plasma in the newly added flux tubes in response to the sunward-directed pressure gradient and the tailward decrease of the magnetic field strength led to a boundary layer flow. Reconnection after prolonged occurrence of northward IMF was intermittent at high latitudes between closed magnetospheric flux tubes and magnetosheath flux tubes. The boundary layer had a reduced speed relative to the adjacent magnetosheath, but was much larger than the velocity in the rest of the magnetosphere closer to Earth. The observable magnetopause, i.e., the region with the largest magnetic shear, was at the flanks and at high latitudes of the tail outside the open-closed boundary. The region between the magnetopause current sheet and the open-closed field line boundary was a region containing highly stressed, recently reconnected IMF field lines. Since these field lines have a history of having been connected with the Earth, they should contain a mixture of solar wind plasma and magnetospheric plasma immediately inside the current sheet. Fairfield (1993) has actually reported ISEE 3 data from 225 R_E behind Earth during periods of northward IMF, where the spacecraft was intermittently in hot, low-density regions and cooler, denser regions with a density intermediate between the magnetosheath and the magnetotail (plasma sheet). The latter region may correspond to the layer of recently created IMF field lines within the region of large magnetic shear.

While the simulation by Fedder and Lyon (1995) applies to the theoretically interesting ground state for the solar wind-magnetosphere interaction, global simulations by Ogino et al. (1994) and Raeder et al. (1995) are better applicable to the evolution and dynamics of the distant magnetotail after a northward turning of the IMF following prolonged southward IMF. Figure 2 shows results from simulations by Ogino et al. (1994). The left side shows flow vectors in the equatorial plane 45 min after the northward turning of the IMF; the right side shows a latitude and longitude mapping along field lines onto the equatorial plane in the tail. The lines correspond to equatorial crossing points of field lines starting at constant latitude or constant longitude, respectively. The field lines crossing the equatorial plane within the region given by the heavy line are closed. From Figure 2 the convection of newly closed field lines around the flanks of the magnetosphere and in toward midnight can clearly be seen. Richard et al. (1994) have attacked the problem of particle entry under northward IMF by calculating particle trajectories in the Ogino et al. (1994) 3D global MHD model. Particles were launched from the solar wind; they entered mainly near the cusp reconnection regions and formed a LLBL. The particles were subsequently undergoing bounce motion on magnetospheric field lines and drifted behind the terminator into the center of the plasma sheet. Thus these particles would be sufficient to generate a dayside LLBL, but could not generate a boundary layer at the distant flanks of the tail. Although the method of following test particles in fields obtained from MHD simulations is an important one, care should be taken when these test particles are not suprathermal compared to the plasma in the MHD run: in the MHD simulation the plasma is assumed to be confined to the flux tubes, whereas in the test particle approach the particle is allowed to gradient and curvature drift. The simultaneous problem of cusp reconnection and boundary layer formation can ultimately only be solved by kinetic simulations.

Raeder et al. (1995) also found that the reconnection-produced newly closed field lines at the dayside are swept by the magnetosheath flow along the magnetopause and are stretched along the flanks of the tail. The momentum flux of the magnetosheath is supposedly so large that the field lines become stretched to at least 400 R_E downtail. These stretched field lines constitute a tailward-flowing layer with closed field lines, i.e., with positive B_z, while there may still exist negative B_z near the tail axis from earlier or still ongoing near-Earth reconnection. This tail flank boundary layer (TFBL) seems not to be driven by a process similar to the one proposed by Song and Russell (1992) where thermal energy is converted into dynamic energy; rather, the momentum of the magnetosheath flow in a newly produced closed flux tube propels the flux tube downstream. Solar wind flow energy is converted by this process into electromagnetic energy by the stretching and twisting of the flux tubes. Recently, Raeder et al. (1997) have directly compared results from the global magnetospheric MHD simulations with observations of plasma and magnetic field in the magnetotail by GEOTAIL. The observed plasma sheet flow at about 50 R_E in the magnetotail was tailward while the magnetic field was northward. The WIND spacecraft monitored the solar wind and IMF upstream of the bow shock. The IMF was northward with a substantial B_y component. According to the simulations for these solar wind input parameters, high latitude reconnection also leads in this case to closed dayside flux tubes, which are carried by the momentum of the magnetosheath plasma downtail.

3. The Low Latitude Boundary Layer on Open Field Lines

There is ample evidence for the existence of a low latitude boundary layer on open field lines during southward IMF. Gosling et al. (1990) found accelerated beams of cold ions sporadically within the LLBL. Because of the low temperatures and the compositional abundance in these beams they must ultimately be of ionospheric origin. Gosling et al. (1990) dismiss reflection at the magnetopause but favor acceleration by the large electric drift of recently reconnected field lines. Fuselier et al. (1991) analyzed He^+ and He^{2+} ion distribution functions near the magnetopause and found that inside the magnetopause the cold ion beam distribution and the transmitted magnetosheath distribution could be transformed by a velocity tangent to the magnetopause such that the resulting distributions were field-aligned and had a flow velocity of the order of the local Alfvén speed. Smith and Rodgers (1991) found D-shaped field-aligned phase space distributions of magnetosheath plasma earthward of the magnetopause. The observations by Fuselier et al. (1991) and Smith and Rodgers (1991) are consistent with the predictions by Cowley (1982) from a kinetic description of reconnection.

Recently Lockwood and Hapgood (1997) analyzed a reconnection event (flux transfer event) in terms of the Hapgood and Bryant (1990) transition parameter. This parameter is based on electron temperature and density behaviour near the magnetopause. Lockwood and Hapgood (1997) could show that in a specific case (flux transfer event) the transition parameter orders magnetopause data because magnetic reconnection generates newly-opened field lines which coat the bound ary. Since the transition parameter quite often orders magnetopause data Lockwood and Hapgood suggest that some newly opened field lines coate the magnetopause most of the time and that these form most of the LLBL. An explanation in terms of reconnection is of course not the only possibility to interpret the relation found between density and pressure. As discussed in the previous section, also under northward IMF recently reconnected and open field lines may be draped around the tail magnetopause and may constitute part of the LLBL. It is an open question to what extent the LLBL is on open and on closed field lines.

4. The Problem of Diffusion

Because of the mutual topologies of the draped IMF and the warped magnetospheric field, there is probably always reconnection somewhere at the magnetopause, leading to free plasma entry. Only when the sheath magnetic field is purely northward may diffusion be assumed to explain the filling of the LLBL at the flanks.

One generally expects that the diffusion would be strongest near the nose of the dayside magnetopause because there the gradients in both density and magnetic field as well as the gradient in plasma temperature are highest. These gradients become much weaker towards the flanks of the magnetosphere. Since classical viscosity is clearly ruled out, diffusion is usually based on gradient driven non-classical processes, drift and current instabilities. These should be weaker or marginal at the flanks.

The experimental investigation of the anomalous diffusion process has not given support to theories based on diffusive particle transport from the solar wind into the LLBL. Early estimates by Eviatar and Wolf (1968), Tsurutani and Thorne (1982) and Gendrin (1983) gave sufficiently high diffusivities for diffusion to be efficient enough to feed the LLBL during periods of northward IMF. But more precise analyses of wave observations by Tsurutani et al. (1989) and Treumann et al. (1991) showed that the wave intensities in the transition layer are not high enough, implying that the instabilities are not strong enough to yield the required anomalous collision frequencies. Figure 4 shows a summary of the dependencies of the diffusion coefficients $D(|\delta E|^2)$ on the intensity of the average electric wave field. In this log-log representation the diffusion coefficients are linear functions of

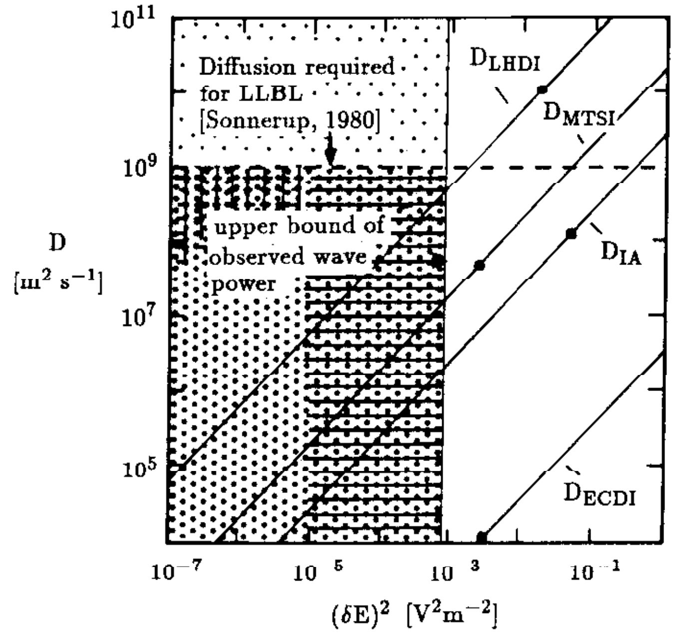

Figure 4. Microscopic diffusion coefficients in the LLBL based on anomalous collision frequencies caused by various drift instabilities: the electron cyclotron drift instability ECDI, the ion acoustic current driven mode IA, the modified two stream instability MTSI, and the lower hybrid drift instability LHDI (after Treumann et al., 1991).

the wave intensity. The horizontal line at $D \approx 10^9$ m^2s^{-1} is the canonical value of the diffusion coefficient required for the filling of the LLBL [see e.g., Sonnerup (1980), who found that only by assuming a value that high he was able to reproduce the width of the LLBL in his model of the magnetopause and boundary layer]. Not entirely surprisingly this value turns out to coincide with the Bohm diffusion coefficient in the LLBL, the presumably highest value classical diffusion can reach in a plasma. The vertical line at about $|\delta E|^2 \approx 10^{-3}$ V^2m^{-2} is at the extreme upper limit of electric-wave intensities ever measured in the LLBL gradient regions (Treumann et al., 1991; Cattell et al., 1995). The region left to this line and below the Bohm-Sonnerup limit corresponds to realistic values of the diffusion coefficients. For acceptable wave intensities none of the diffusion coefficients comes close to the Bohm-Sonnerup limit. Hence, under most conditions diffusion based on anomalous collision frequencies is unable to build up the LLBL. The most promising positive exception is the lower hybrid drift instability (LHDI). Sporadic, very high wave intensities in this wave mode may cause strong plasma injection. But the reduction in the density profile produced in the diffusion should keep the instability and diffusion at their marginal values. Note that the theoretical quasilinear saturation limit of the instability (full dots) for the LHDI even exceeds the Bohm- Sonnerup diffusion limit by an order of magnitude. For the other wave modes these limits are generally higher than any measured wave intensity, indicating that the available nonlinear theories grossly overestimate the saturation amplitudes. The particular case of the LHDI is of interest because it may suggest that wherever the LHDI is effective in transport across the magnetopause current layer it will be strong enough to deplete the density profile so much that a marginally stable state will be readily reached with flat profiles and marginally but still high wave intensities near the lower hybrid frequency. Theoretically highest diffusion coefficients could be twice the Bohm value. But this will quickly reduce to the marginal state.

A statistical analysis of the wave intensities in the vicinity of the magnetopause performed by Treumann and Bauer (1996) and reproduced in Figure 4 shows the electric wave intensities averaged over a large sample of AMPTE/IRM magnetopause crossings. The low (high) shear wave intensity maximum ($< 10^{-7}$ V^{2}m^{-2}) is at the sheath-LLBL (inner edge) transition and yields extremely small average diffusion. Based on these observations, diffusion can only be *marginally high in microscopic localized regions*, presumably LH density cavitons which escape the measurement but have theoretically been predicted to exist (Shapiro et al., 1993, 1995). Formation of density cavities by other processes as ion holes, large-amplitude ion sound waves, low-frequency ion-beam driven waves and others may also have the effect of wave trapping, anomalous diffusion and acceleration. The position of the wave maximum in Figure 4 may provide evidence for the last closed magnetic field line as is frequently believed. Indeed, it is possible that the magnetopause is partly a tangential discontinuity, with reconnection taking place at a remote location. But this may just imply that the inner edge field line is connected to the reconnection site, as suggested by Lockwood and Smith (1994). On the other hand, this conclusion is uncertain as long as it cannot be supported by other evidences. In particular, it is surprising that for the high shear cases in Figure 4 the intensity maximum is at the inner edge of the LLBL and not at the magnetopause where it is believed that reconnection takes place. This may imply that the maximum intensity is caused by something else than reconnection, for instance simply by the density gradient which is steepest at the inner edge for high shear and at the magnetopause for low shear. Hence, it cannot be excluded that the Lockwood-Smith picture is true and that the magnetopause crossing in low shear cases is simply at a position where the magnetopause was a piecewise closed fraction of a tangential discontinuity and reconnection took place at a remote location. The low value of diffusivity determined from the intensity maximum seems not to contradict this claim.

Numerous numerical simulations of diffusive LLBL formation have been carried out by Berchem and Okuda (1990), Cargill and Eastman (1991), Drake et al. (1994), Gary and Sgro (1990), Winske and Omidi (1995), Omidi and Winske (1995), Winske et al. (1995), and others. All these simulations demonstrate that in two dimensions the magnetopause current layer is erased by LHD instabilities and widens under the action of the LHDI. But, as shown by Winske et al. (1991), its

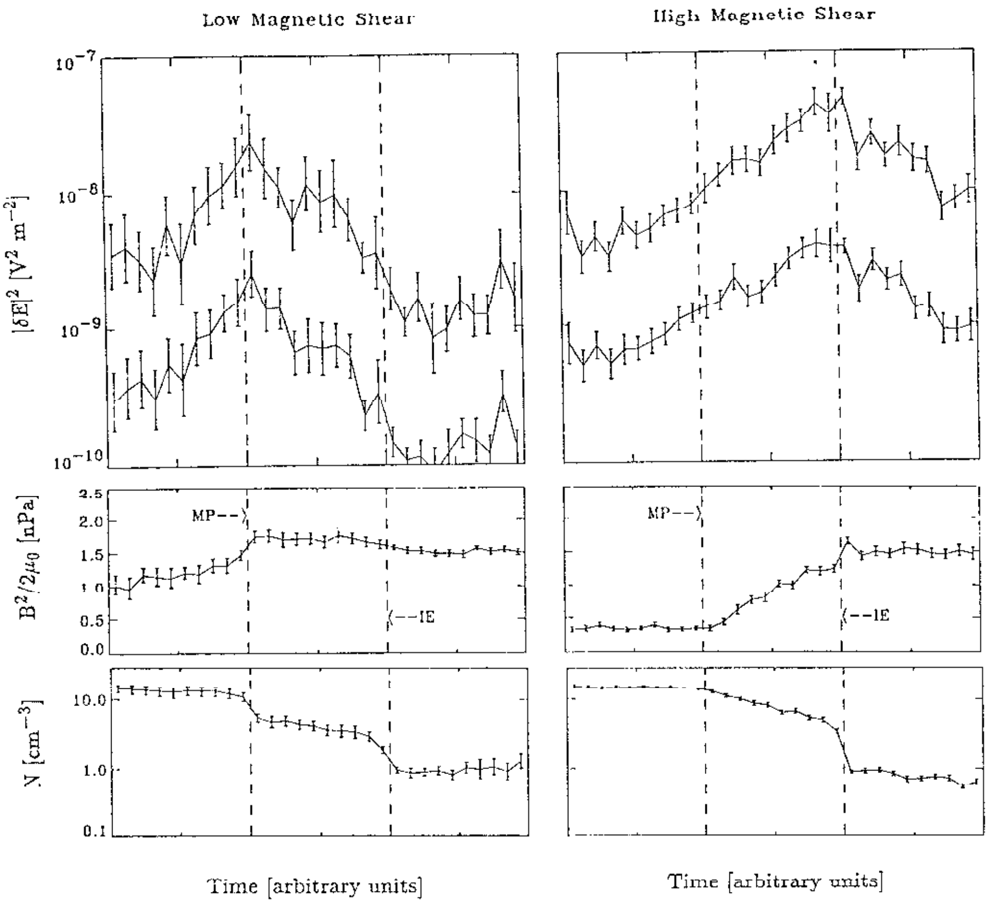

Figure 5. Superposed epoch representation of ensemble averaged wave intensities in the magnetopause transition as function of position relative to the magnetopause current layer for low and high shear conditions. The abscissa is the time axis corresponding to the crossing of the boundary layer by the spacecraft. The left vertical line is at the position of the nominal magnetopause current layer, the right vertical line is at the position of the inner edge of the LLBL. The frequency range contains the lower hybrid frequency. The upper curve is the ensemble averaged wave peak value within 1 s of measurement, the lower the 1 s average of the wave intensity. The maximum in the wave intensity is found at the current layer for low and at the inner edge of the LLBL for high shear.

spread is only slightly more than an ion gyroradius not comparable to the width of the LLBL. The initial diffusion is fast, about 30% of Bohm diffusivity, but outside the steep gradient region quickly drops to low values. Some more energetic particles diffuse over a larger distance and the diffusion coefficient calculated from the arrival time of the first of these particles is Bohm-like. But estimates using the shape of the density profile (Treumann et al., 1992) fix it at a value one order of magnitude below Bohm-Sonnerup and suggest that the first, fast particles are just the resonant ones, the phase space volume occupied by which is negligible, as has been shown by Dum (1996).

Anomalous diffusion is not the only way out of the diffusion paradox/dilemma. It has been argued recently by Treumann and Bauer (1996) that "superdiffusion" may exist in plasmas containing nonthermal (generalized Lorentzian or κ) electron distribution functions. Traver et al. (1991) and Christon et al. (1988) have occasionally measured such distributions in the magnetosphere, and Lin (1997) reported their existence in the solar wind. Distributions like these resemble the probability distributions which Shlesinger et al. (1993) use in the description of Lévy flight interactions. Recently, Treumann (1997) has developed a theory of superdiffusion based on the Lévy flight model. The super diffusion coefficient approaches the Bohm limit. The most interesting fact is that the diffusion becomes not only strong but in addition is time dependent. Consequently, the density profiles loose their diffusive shapes. However, super-diffusion is heavily dependent on the presence of long-range turbulence in the plasma which causes non-stochastic interactions between the particles or the particles and waves. It can thus be expected only in regions of high levels of turbulence.

According to Mace et al. (1997) the thermal fluctuation level of plasma waves in a plasma containing κ distributions is increased by several orders of magnitude over the usual fluctuation level. The reason for this increase can be found in the high energy tail of the distribution function. Though the tail particles themselves run away, the high fluctuations caused by them scatter the thermal bulk plasma component at a much stronger level thereby increasing the collision frequency. At the magnetopause this factor can be as high as 10^{4-6} (Treumann and Bauer, 1996), such that the nonthermal collision frequency becomes of the order of $\nu \sim 0.1 - 10$ Hz, which is a substantial fraction of the lower hybrid frequency, $f_{lh} \approx 50$ Hz. In such extreme cases diffusion becomes close to Bohm-Sonnerup and may cause increased plasma inflow. But again, since these effects are restricted to the regions of high levels of plasma turbulence which may cause the distribution function to deviate from the Maxwellian and become a κ distribution, one expects that the super-diffusion will be restricted to localized regions only.

Anomalous diffusion based on low frequency magnetic fluctuations has been ruled out (Tsurutani and Thorne, 1982). If the low frequency waves measured near the hydrogen ion cyclotron frequency f_{ci} by Rezeau et al. (1993) are indeed kinetic Alfvén waves, in particular kinetic Alfvén solitons, then they are another candidate, as suggested by Lee et al. (1994), Lotko and Sonnerup (1995) and more recently on firmer grounds by Johnson and Cheng (1997). Figure 4 shows magnetic power spectra from IRM transitions of the LLBL. The f_{ci} emission is the sole property of the inner edge (IE) of the LLBL probably caused by the electromagnetic ion-cyclotron instability when the cold LLBL plasma mixes into the hot ring current protons. The LLBL spectra exhibit an unstructured power law ($\propto f^{-2.4}$) with higher intensities in the right- and left-hand polarized modes than in the compressive part, indicating scale-invariant, weakly compressible magnetic turbulence below $f < f_{ci}$. The integrated intensities of these waves are not overwhelmingly high but appreciable. It is not known, how far the spectrum extends towards low frequen-

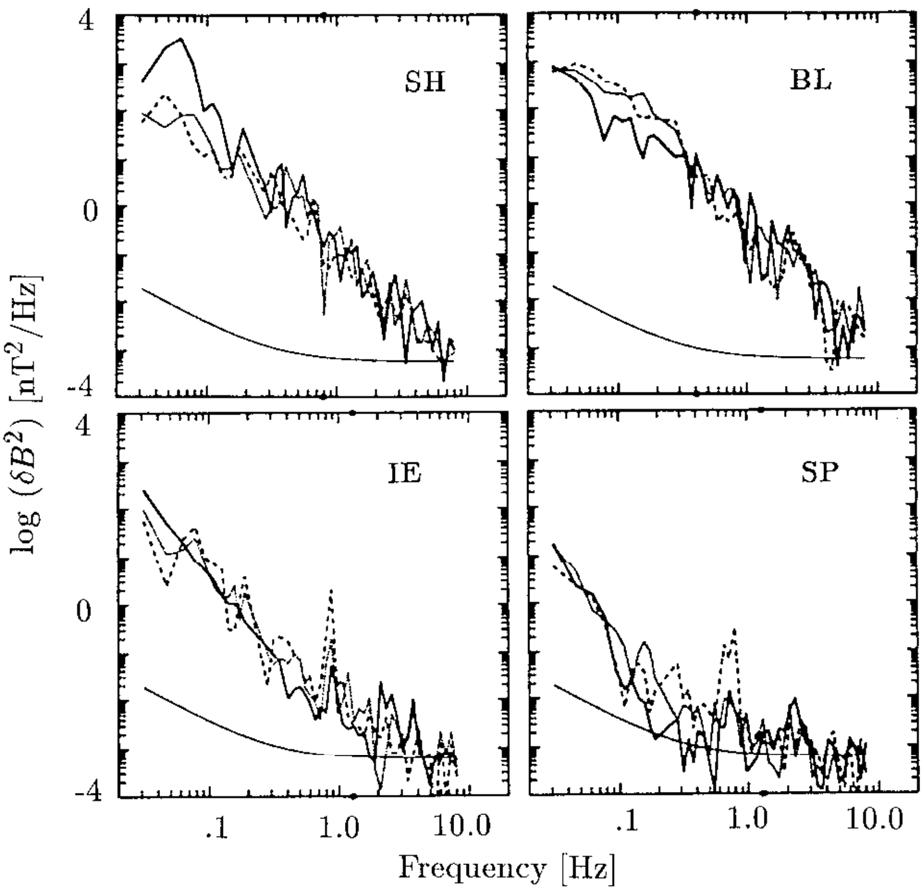

Figure 6. Average IRM magnetic low frequency power spectra in the magnetopause transition as function of frequency (after Treumann et al., 1995). The ion cyclotron line is found only in the LLBL-sphere transition part. Otherwise, the LLBL spectra have structureless power law behavior with low compressive part and about equal left and right circularly polarized intensities (dotted: left polarized, thin: right polarized, heavy line: parallel polarized).

cies. But the total wave amplitudes may be as high as 1 nT and may contribute to transport. However, since for these low frequencies the first adiabatic invariant is conserved, diffusion can only be caused by scale invariant turbulence.

Scale invariance implies that left- and right-handed magnetic vortices exist on all scales and hence mix and overlap and stochastically reconnect. It has been realised that a fluctuating magnetic field lacks a well-defined identity and may migrate across the turbulent region. Percolation theory (Isichenko, 1992) provides the basic physics. This theory has been applied to the magnetopause by Galeev et al. (1986) and Milovanov and Zelenyi (1995). An early estimate of the geometric diffusion coefficient given by LaBelle and Treumann (1988) yielded a value close to Bohm diffusion. Milovanov and Zelenyi (1995) have shown that inclusion of finite-ion Larmor radius effects even increases this type of diffusion. In this model the stationary LLBL for northward IMF should resemble a mixture of many overlapping magnetic islands forming channels (wormholes) where field lines or plasma can locally migrate. The magnetic channels have the properties of magnetic holes as discovered by Lühr and Klöcker (1987) in the magnetic field and Treumann et al. (1990) in plasma waves at the magnetopause. Sonnerup and Guo (1997), solving the two-dimensional Cauchy problem for the internal magnetic structure of the tangential discontinuity magnetopause using IRM data, found both islands and wormholes in the transition region.

5. Kelvin-Helmholtz Instability

The magnetopause and LLBL are regions of fast shear flows. The velocity shear is particularly strong at the flanks of the magnetosphere with the anti-sunward flow velocity in the adjacent magnetosheath presumably reaching supermagnetosonic values and the general magnetospheric convection flow being in sunward direction. Such configurations are traditionally unstable with respect to the Kelvin-Helmholtz instability (e.g., Chandrasekhar, 1961). This instability causes convective growth of a surface wave leading to undulations of the magnetopause and in the LLBL and is believed to contribute to momentum exchange and possibly also mixing between the sheath and magnetospheric plasmas. In the framework of magnetohydrodynamic theory the KHI provides merely momentum transport since it is a macroinstability. The electrons are frozen to the magnetic field and the ions follow them via the ambipolar electric field. In order to obtain mass transport across the magnetic field, some mechanism must break off this siamesian twinning relationship between particles and field. Until today it is not known of what kind such a mechanism would be as long as one is not leaving the fluid dynamic picture and does not refer to microinstabilities causing diffusion or to reconnection driven by the KHI. Both of these are possible, however, but on the cost of assuming that the KHI generates short scale vortices of the order or shorter than the ion gyroradius and thus violates the fluid picture. Below we will comment on simulations which indicate some mass transport.

Experimental evidence for the KHI has been reported by Ogilvie and Fitzenreiter (1989), Sckopke et al. (1981), Takahashi et al. (1991) and others. Figure 5 shows the model of the near-dayside LLBL inferred by Sckopke et al. (1981) from ISEE observations. This event had positive and negative IMF B_z-components. Its transition region is composed of the non-transparent magnetopause and an oscillating LLBL attached to its inner part that is driven by the velocity shear and evolves into traveling vortices (as shown in the equatorial section of the magnetosphere). At the dayside obviously these vortices convect tailward with the general sheath flow direction. Note that this model implies mass or momentum transport at the

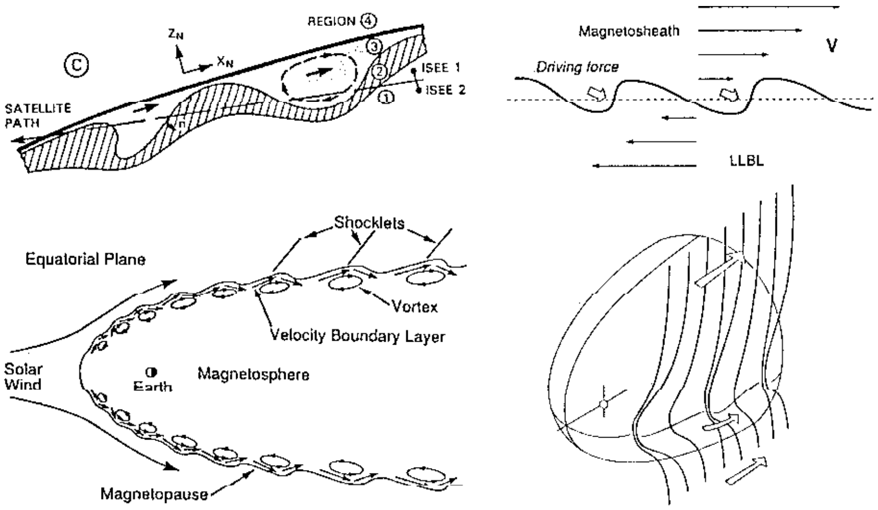

Figure 7. Model of LLBL undulations caused by the Kelvin-Helmholtz instability inferred from two-spacecraft (ISEE 1 & 2) observations (upper left. Sckopke et al.. 1981) with a smooth undistorted magnetopause and oscillating LLBL. Regions 1-4 denote sphere, inner and outer LLBL, and sheath, respectively. Below: The corresponding equatorial section of the magnetosphere as inferred from MHD simulations (Miura, 1992). Upper right: Observed driven KH-vortices and (below) a possible magnetic driver model (Chen et al., 1993).

inner edge of the LLBL only! But as shown by Miura (1992, 1995b) and Thomas and Winske (1991, 1993) this may be misleading because any vortices generated at the magnetopause by the external shear flow will be readily transported into the deep LLBL and may have distorted the observations. Ogilvie and Fitzenreiter (1989) found, checking the KHI condition, that KHI can indeed evolve at the inner edge of the LLBL. Another check of the KHI criterion has been provided for a large sample of magnetopause crossings by Seon et al. (1995) at the far ($\sim$ 30 R_E) dawn magnetopause flanks. They found that the entire magnetopause becomes unstable here for high solar wind velocities independent of the IMF direction while for low speeds the excursions of the LLBL are non-oscillatory and rare. However, the growth rate of the KHI is close to marginal, implying nonlinear saturation. During an extended interval of northward IMF, Chen et al. (1993) found that at the dawn flank of the magnetotail the entire magnetopause-LLBL system oscillated at a $\sim$5 min period with tailward directed wave vector. The wavelength was between 5-15 R_E, and the wave form was found to be non-sinusoidal, indicating steepening or driving, with an amplitude of 10% of the wavelength. The shape of the oscillation suggests some driver mechanism (see Figure 5). For strong compression of the magnetosphere, Takahashi et al. (1991) reported regular short-wavelength 50 s-period oscillations generated in the LLBL.

The interesting question is whether and to what degree the KHI contributes to transport (momentum, mass mixing) across the magnetopause. So far this question has not been answered from observations. Also, the many numerical simulations performed give only ambiguous results. Miura (1982, 1984, 1992, 1995a, b) used a periodic (and hence somewhat unrealistic) compressible ideal 2D-MHD simulation scheme. KHI increased up to saturation forming large but non-coalescing vortices leading to broadening of the velocity transition layer. The broadening factor depends heavily on the direction of the magnetic field and is largest (~ 3 times the initial width) for northward IMF, dropping to about ~ 1.8 for magnetic shear angles $\gtrsim 60°$ (Miura, 1995a). The broadening suggests formation of a velocity boundary layer of rather too narrow width. Clearly, KHI provides momentum transport from the sheath to the LLBL. Steep profiles in the fluid momenta are caused at the boundaries of the vortices by nonlinear steepening which resembles shocklets. Of course, these fluid simulations are realistic only as long as the steepening is of a scale considerably longer than the ion gyroradius r_{ci}. Miura (1982) argued that in the steep field and density gradients anomalous viscosity and dissipation arise from anomalous magnetic stress and can be as large as $\gtrsim 0.03 r_{ci} v_{\mathrm{th}i}$, a comparably high viscosity. Wu (1986) challenged this result by performing a convective nonperiodic simulation. Both cases, parallel and perpendicular flow, are unstable with coalescing vortices, but the instability grows only in the far tail and is not important at the near-Earth flanks. Similar simulations by Manuel and Samson (1993), applying nonperiodic in- and outflow, yield faster convective growth, turbulent boundary layers and transport of momentum and energy from the sheath into the LLBL. The LLBL widens towards the flanks by a factor of ~ 6, somewhat larger than Miura's results. As a consequence, these authors, for realistic LLBL conditions estimating the Reynolds stresses in the same way as Miura (1982), obtain an enormous viscosity of $\gtrsim 10^{10}$ m^{2}s^{-1}. They also find mass transport which in the fluid model is difficult to explain. This raises doubts as to the validity of their simulations. Recent 2D fluid simulations performed by Huba (1994, 1996) include Hall-MHD (Huba, 1994) and finite Larmor radius (FLR) (Huba, 1996) effects. Inclusion of the Hall term causes an asymmetry in the vortices produced by the KHI at the dawn and dusk flanks of the magnetopause as well as also enhanced momentum transport. The inclusion of FLR effects taken into account in the anisotropic ion stress tensor results in an anisotropic evolution of the vortices, generation and detachment from the vortices of plasma blobs and thus bulk mass transport, and more complicated nonlinear evolution leading to turbulent mixing. The anisotropy results from the dependence of the nonlinear evolution on the vector product between the diamagnetic ion drift and the vorticity with the latter being of different signs at the dawn and dusk flanks (see Figure 5). The transport of blobs is from the high- into the low-density region (sheath to LLBL), but not vice versa. The physical mechanism, if realistic and not caused by numerical residual resistivity, is not entirely clear. The evolution of the KHI vortices would, in the nonlinear stage, result in some kind of interchange between flux tubes. FLR effects may indeed resemble some kind of quasi-gravitational effect which may affect a heavily mass loaded flux tube to undergo interchange with a lighter one. Investigation of this effect and finding the appropriate nonlinear equations is an interesting but unresolved problem.

The results of the FLR simulation resemble those of recent hybrid simulations performed by Thomas (1995), who also found blob formation, possible dawn-dusk asymmetries and seemingly also mixing. Another important hybrid simulation has been presented by Terasawa et al. (1992) and extended by Fujimoto and Terasawa (1994), who showed that, in a massless electron fluid with particle ions, the nonlinear evolution of the KHI on time scales longer than the vortex roll-up time leads to scattering of ions deep into the LLBL. If realistic, this would imply fast mass transport in hybrid simulations of the KHI. Such simulations treat the electrons as a fluid, usually a massless fluid which is frozen to the magnetic field. The mass transport should in this case be entirely due to deviation of the ion motion from that of the electrons. One expects that this will be possible only for a few nonthermal ions in the tail of the distribution function having sufficient energy to resonate with the smallest vortices produced in the high phase velocity of the KHI and therefore should not be an important effect. Thus mass transport should be negligible. The amount of transported mass found in the simulations seems to be much higher, however. The authors propose that the physical mechanism is chaotic ion scattering at the fluctuating electromagnetic fields connected with the nonlinear evolution of the KHI, a process which has not yet been clarified theoretically. This finding, if confirmed, suggests that KHI at the flanks of the magnetopause might be more important for particle transport than generally believed. Solution can be expected from two sides, either an appropriate nonlinear kinetic treatment or a full particle simulation. Kinetic treatments are not available yet.

A 2D-full particle three-velocity simulation has recently been reported by Wilber and Winglee (1995). This simulation is promising as a first step into a more precise kinetic picture of the KHI at the magnetopause flanks. The main result, which Wilber and Winglee (1995) obtain, is that the nonthermal differences in the motions of electrons and ions may lead to plasma mixing and transport even in the KHI, which otherwise is not included in MHD simulations. Discrete intense current layers are formed at steep gradients confirming the fluid simulations of Miura (1982) and extending them to narrower scales. The plasma generates tongues which penetrate the field region and may decouple from the plasma source region, which in this case is the magnetosheath. In addition there are asymmetries between the dawn and dusk sides of the magnetosphere with plasma penetration stronger on the dawn side. The reason is found in the differences of the electron and ion dynamics on both flanks. One may conclude from these simulations that the microscopic dynamics of the plasma has a strong effect on the KHI causing plasma mixing which is not contained in any of the fluid dynamic treatments.

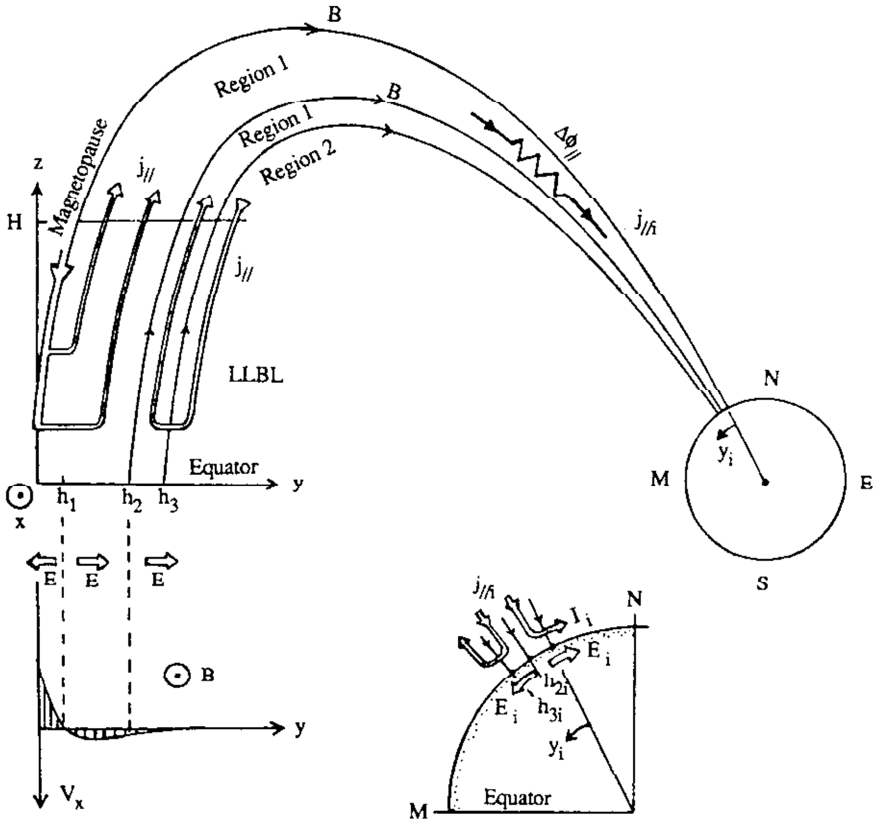

Figure 8. Schematic drawing of the dawnside low-latitude boundary layer and its coupling to the auroral ionosphere, including a field-aligned potential drop $\Delta\Phi_{\parallel}$. Pedersen currents and electric fields in the ionosphere are shown in the insert (from Phan et al., 1989).

6. Viscous Boundary Layer: Coupling to Ionosphere

The plasma motion in the LLBL is coupled to the ionosphere, through field-aligned currents (FACs), which in turn has implications for the momentum balance in the layer. The motional electric field in the layer maps more or less along geomagnetic field lines to the ionosphere where it drives perpendicular Hall and Pedersen currents. When the divergence of the ionospheric perpendicular currents is non-zero FACs that flow along the closed geomagnetic field lines arise (region 1 currents). Because of the hemispherical symmetry these currents close as perpendicular currents in the LLBL where they produce a $\mathbf{j} \times \mathbf{B}$ drag force impeding the plasma motion. Sonnerup (1980) developed the first one-dimensional steady state model for a viscous slab-type LLBL. In the Sonnerup model the ionospheric drag is balanced by the viscosity in the boundary layer, which couples the boundary layer flow to the magnetosheath flow. Figure 6 shows a view from the sun on the dawnside boundary layer and its coupling to the ionosphere, including a field-aligned potential drop. The boundary layer occupies a region $| z |< H$ in which the plasma velocity $v_x(y)$ is shown. Pedersen currents and electric fields in the auroral ionosphere are shown in the insert. The drag produced by the ionosphere in the LLBL depends on the total ionospheric Pedersen conductivity, the magnetic field intensity in the ionosphere relative to the intensity in the LLBL, and the magnetic field mapping factor, which accounts for the divergence in the flux tube dimensions (the ratio of a length segment in magnetic local time in the ionosphere to its mapped length segment in the streaming direction in the LLBL). The Sonnerup (1980) model has in the meantime been considerably extended: the model showed that the FAC generated by the LLBL dynamo must be limited by a field-aligned potential if the ionospheric signature is to match observations. Lotko et al. (1987) have allowed for field-aligned potentials by including a conductance law to describe the relation between field-aligned currents and field-aligned potential drops. In these models the magnetic fields induced by the FACs were not included. Phan et al. (1989) have developed a self-consistent one-dimensional model of a viscous LLBL in which the magnetic field deformation in the layer by the currents is included. It is shown that the field lines in the LLBL take on a parabolic shape with the vertices pointing in the downstream direction. Such a tailward distortion has been reported by Eastman et al. (1985) and may impede the Kelvin-Helmholtz instability. The field line curvature is greatest at the magnetopause edge of the layer and vanishes at the magnetospheric edge. The Phan et al. model is, like the Sonnerup (1980) and Lotko et al. (1987) model, one-dimensional in the sense that it does not allow for variations of the layer in the flow direction but only in the direction normal to the magnetopause.

Recent new developments and improvements of the Sonnerup (1980) model of the LLBL-ionosphere interaction include the models by Drakou et al. (1994) and by Wei et al. (1996). The model by Drakou et al. (1994) is a 2 D model which self-consistently determines the magnetic field change by the currents, like the Phan et al. model, but allows for variations in the layer streaming direction (x) parallel to the magnetopause. It should be noted that in this model entry of magnetosheath plasma into the LLBL is assumed to be at the dayside and not along the flanks; along the flanks the layer is viscously driven by the magnetosheath flow. The model describes the increase of the field-aligned region 1 current density with magnetic local time (two hours before and after noon, Iijima and Potemra, 1978), and the increase of latitudinal width of the FAC system with increasing longitudinal distance away from local noon. The latter is due to viscous entrainment of magnetospheric plasma in the equatorial plane to participate in the tailward flow of the dense LLBL. Wei et al. (1996) have extended the Drakou et al. model by allowing for a field-aligned potential drop and by including constant magnetosphere-ionosphere mapping factors. The model correctly predicts the increase of the width of the FAC channel in the ionosphere with local time, and results in a field-aligned potential drop of up to 3 keV.

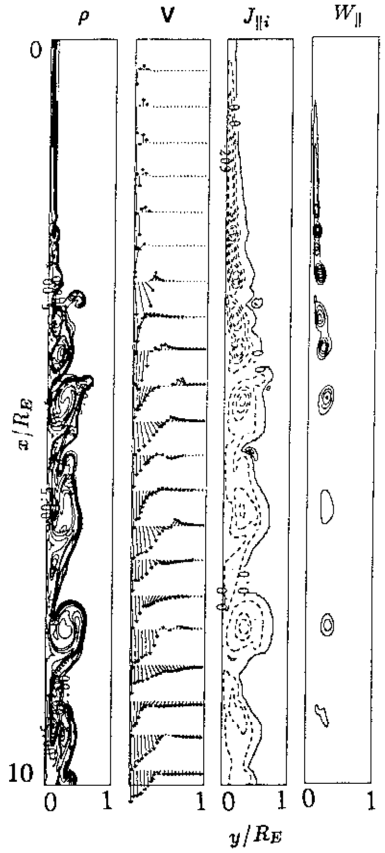

Figure 9. Contour plot of plasma density, vector plot of flow velocity in the magnetosphere, contour plot of field aligned current density, and contour plot of field-aligned power density for a postnoon boundary layer simulation (from Wei and Lee, 1993).

Plasma transport across the magnetopause has been included in a viscous model of LLBL-ionosphere interaction by Wei and Lee (1993). A field-aligned potential is allowed to accelerate electrons parallel to the field, and the ionospheric Pedersen and Hall currents are allowed to be enhanced due to precipitating electrons in the upward FAC region. Plasma transport across the magnetopause is assumed to be diffusive; this diffusive transport is incorporated in the model by a constant velocity v_y of the order of 2-10 km/s normal to the model magnetopause boundary. The tangential velocity at this boundary is kept at its magnetosheath value. It turns out that the driving of the plasma flow in the boundary layer leads to the formation of Kelvin-Helmholtz vortices that grow to large size as they are convected tailward. The vortices lead to localized current flows into or out of the polar ionospheres. The competing effect of the formation of the vortices in the boundary layer and dissipative decay of the vortices by the ionospheric conductivity leads to the formation only in limited regions. The enhanced conductivity in the postnoon auroral oval due to the upward FACs allows strong vortex formation and correspondingly localized regions of large FAC densities. The enhanced regions of the field-aligned power density are associated with auroral bright spots resembling beads or pearls (Lui et al., 1989). Figure 6 shows contour plots of the plasma density, vector plot of the flow velocity, contour plots of the field-aligned current density and contour plot of the field-aligned power density for the postnoon boundary layer simulation. The subsolar point at $x = 0$; $y = 0$ is the location of the magnetopause.

7. Summary

Observations and simulations both overwhelmingly support the view that reconnection is the dominant process in the formation and maintenance of the LLBL, even for northward IMF conditions. Then reconnection proceeds at high latitudes or non-symmetrically on the magnetopause. Part of the LLBL is probably always on open field lines. During dayside reconnection the entire LLBL is on open fields, while for northward IMF its inner part may be on closed field lines. It seems that under most conditions the flank LLBL is on open fields but asymmetries between dawn and dusk are not excluded.

Concerning anomalous diffusion, six points should be highlighted. (1) Anomalous diffusion is of minor importance for the maintenance of the LLBL, thus confirming the negative conclusion of Russell (1995). However, (2) diffusion is sufficiently high for leakage of resonant particles from the magnetosphere into the sheath, and (3) for locally providing the resistivity required by reconnection. (4) Superdiffusion can reach the Bohm limit but will be highly localized in regions where the parallel electron distribution is a generalized Lorentzian. High-resolution electron and plasma wave measurements are required to check its reality. (5) Coherent low-frequency waves contribute little to diffusion as long as they do not violate the frozen-in and ambipolar conditions. Their effect may be in resonant transport of high energy particles, however. (6) Once the low-frequency waves evolve into scale-invariant low-frequency magnetic turbulence, they may cause island overlap, magnetic wormhole formation and field migration and may be important in maintenance of the LLBL under tangential discontinuity conditions. Clearly macroinstabilities like the KHI can, by producing steep gradients in density, field and current, locally stimulate anomalous transport by means of LHDI and contribution to low-frequency turbulence.

Velocity-shear driven KHI at the magnetopause has not yet been convincingly identified as being important for the presence and dynamics of the LLBL. It is without doubt excited under high-speed northward IMF solar wind conditions, leading to oscillations of the magnetopause and in the LLBL. On the dayside magnetopause near the stagnation region it seems if present to dominate at the inner edge of the LLBL, while at the flanks it embraces both regions though possibly in an asymmetric way. Simulations and observations still yield ambivalent conclusions about its growth and saturation along the magnetopause towards the flanks. Periodic and open-box MHD simulations give contradictory results. Hall and FLR MHD simulations offer a hint about dawn-dusk asymmetry, plasma blob detachment and anomalous transport. Once KHI develops, momentum transport is well established, but estimated viscosities are unrealistically high. It has been claimed but is not clear whether KHI leads to mass transport. For this to happen the KHI must evolve to short wavelengths and affect the electron dynamics. This is not included in fluid simulations and fluid theory and requires but full particle kinetic treatments. Moderate mass transport and plasma mixing are suggested in FLR and hybrid simulations but still require more work for clarification. In particular, it remains unresolved if KHI vortices contribute to eddy transport and coupling of the magnetopause to the inner edge region. Coupling to the ionosphere may cause break-off of large-scale into small-scale vortices leading to a turbulent LLBL and enhanced momentum transport and possibly also turbulent mass transport.

It is our impression that the electromagnetic coupling of the LLBL to the ionosphere is not quantitatively addressed in any available model. The transit time of Alfvén waves from the LLBL to the ionosphere is comparable to the typical times of variation in the LLBL. This may not be accidental but has not yet been accounted for. Field-aligned potential drops and currents between both regions are inevitable and cause asymmetries between the dawn and dusk flanks. Decoupling at dusk by potential drops could favour KHI, while stronger currents at dawn yield turbulent KHI and enhanced fluctuations.

In summarizing, it is still unclear which part of the LLBL is on closed/open field lines and under which conditions, whether the LLBL carries kinetic Alfvén waves as connectors to the ionosphere, what and where the field-aligned potential drops are, and whether or not the flanks are more important for the formation of the magnetopause boundary layer and in the coupling than the dayside LLBL. Clarification of these problems will require a substantial amount of additional experimental and theoretical work as well as all types of numerical simulations.

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