The Impulsive Penetration of Solar Wind plasma elements into Magnetospheres

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The mechanism of Impulsive Penetration of solar wind plasma into the Magnetosphere has been introduced for the first time in 1976, at an EGS symposium on the Magnetopause. It was then considered as an alternative to the two challenging stationary magnetospheric models under debate since over a decade: (i) the c*losed magnetosphere model* with "viscous interaction" driving magnetospheric convection inside the region permeated by closed geomagnetic field lines (Axford & Hines, 1961), and (ii) the *open magnetospheric models* with a southward oriented interplanetary magnetic field superimposed on the dipolar terrestrial magnetic field (Dungey, 1961).

The concept of "Impulsive Penetration" (IP) at the Magnetopause was introduced based on the available observational evidence that the supersonic solar wind (SW) flow and the Interplanetary Magnetic Field (IMF) at 1 AU, are both varying over time scale smaller than the time required for the solar wind plasma to encompass the Magnetosphere. The solar wind plasma was also suspected to be "patchy" over distances that are smaller than the diameter of the Magnetosphere. The lack of stationary and of uniformity of the solar wind leads to the formation of localized pressure pulses (enhancements and depressions) along the Bow Shock surface; the latter propagate across the Magnetosheath impacting the Magnetopause, and shaking continuously the Magnetosphere (Lemaire, 1977; Lemaire and Roth, 1978).

These plasma irregularities are now called plasmoids ("plasma-field entities") due to their similarity with those fired in the early laboratory experiments performed by Bostick (1956, 1957) and others. Indeed, Bostick (1956) who introduced the word "plasmoid" showed that these "plasma-field entities" possess a measurable magnetic moment, a measurable translational speed, a transverse electric field, and a measurable size (Harris et al. 1957). Furthermore, Bostick (1956) showed that plasmoids can interact with each other, seemingly by reflecting off one another. Their orbit can be made to curve toward one another. Laboratory plasmoids can also be made to smash each other into fragments.

Solar wind plasmoids with an excess momentum density penetrate into the Magnetosphere due to a self-polarization electric field ($\mathbf{E}_{pol}$) as first described by Schmidt (1960). This E-field is set up within the moving plasma clouds by surface charges of opposite signs (electrons and ions) that have been deflected in opposite direction by the Lorentz force ($q\ \mathbf{u} \times \mathbf{B}$) and that accumulate on the lateral surfaces of the plasmoids as it proceed across the B-field line with the bulk velocity **u**; the sideward motion of the charged particles in opposite directions generates the so-called polarization currents ($\mathbf{j}_{pol}$); the latter correspond to the displacement currents in classical Electromagnetic textbooks ($\mathbf{j}_d = \partial \mathbf{D}/\partial t$).

The mass density (ρ) of plasmoids is large so that dielectric constant (ε) is much larger than unity $(\varepsilon = 1 + \rho c^2/(B^2/\mu_0) >> 1)$. Furthermore, plasmoids are diamagnetic, especially when the ratio between the kinetic energy density of the plasma and magnetic field energy density is of the order of unity ($\beta \sim 1$); this as it is commonly the case in the Magnetosheath. The presence of diamagnetic plasmoids disturbs the ambient/external magnetic field distribution at the magnetopause in a dynamical way. The dynamical deformation (not motion!) of the

interconnected IMF and geomagnetic field lines has been illustrated in video motion picture produced in 1982 at the Belgian Institute for Space Aeronomy. This animation is available at http://csrsrv1.fynu.ucl.ac.be/csr_web/theory/magnetopause-uk.php .
Thefore the presence of diamagnetic plasmoids distorts the magnetopause surface just like rain drops disturbed the surface of a lake. The effects of diamagnetic currents ($\mathbf{j}_{dia}$) and the induced electric field ($\mathbf{E}_{ind}$) circulating around moving plasmoids have been pointed out by Heikkila (1982). It is clear that the inductive electric fields ($\mathbf{E}_{ind}$) add to the polarization electric fields ($\mathbf{E}_{pol}$) to determine **u**,
the total $\mathbf{E} \times \mathbf{B} / B^2$ convection velocity of the plasmoid.

As a result to their excess momentum solar wind plasmoids drift into the geomagnetic field where they are braked adiabatically (as a consequence of the conservation of the magnetic moment (μ) of all the individual electrons and ions forming the plasmoid). Once embedded in the magnetosphere plasmoids are also slowed down by transferring their excess momentum and kinetic energy to the ionospheric plasma by Joule dissipation in the polar cusp regions.

The Impulsive Penetration (IP) concept differs from the Reconnection one proposed by Dungey (1961), Giovanelli (1948) and others. Indeed IP does not rely on the existence of mathematical singularities in the ambient/external B-field distribution. IP does operate whether the Magnetopause surface is a Tangential Discontinuity or a Rotational Discontinuity, whether it contains or not neutral-lines or X-lines. The physics involved in the Impulsive Penetration mechanism is outlined in the article of Lemaire (1985). His theory is founded on the original description introduced by Schmidt (1960) and soon adopted by Baker and Hamel (1962, 1965), Demidenko et al. (1967, 1969, 1972), Lindberg (1978) to explain the results of their laboratory experiments.
Echim and Lemaire (2000) reviewed these early laboratory experiments, as well as some numerical simulations of the impulsive penetration mechanism.
In-situ satellite observations of Magnetosheath-like plasma engulfed in the magnetospheric Boundary Layer have been described by Lundin (1988). More recent studies of the Impulsive Penetration mechanism in laboratory plasmas have been published by Hurtig et al. (2003, 2004, 2005) , Brenning et al. (2005), Gunell el al. (2008, 2009).

I will discuss these theoretical and laboratory results that support the IP concept. The adiabatic deceleration/acceleration of plasmoids in non-uniform B-field, will be recalled, as well as their non-adiabatic braking by Joule dissipation of their excess momentum into the underlying ionospheric polar cusp regions. The eastward deflection of plasmoid penetrating into the geomagnetic field, and predicted by the IP mechanism will be pointed out.

I will also present the kinetic solutions of Vlasov-Maxwell equations simulating the motion of two-dimensional plasmoids across a transverse magnetic field obtained by Marius Echim as part of his Ph.D. thesis (*http://hdl.handle.net/2078.1/20730* ; Echim, 2004 ; Echim et al., 2005). I will emphasize the role played by parallel electric fields decoupling the penetrating blobs from the background plasma and fields.

Finally, I will show why the ion to electron temperature ratio (T_e/T_i) does not necessarily vary while a solar wind plasmoid drifts adiabatically across the Magnetopause. Recent CLUSTER observations by Lavraud et al. (2009) confirm that the values of T_e/T_i observed in the Magnetosheath are comparable to those measured by CLUSTER inside plasmoids engulfed on the adjacent Magnetosphere.

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