Descriptions.doc

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1. File#1 (File_1.gif) is an animation of Gold's (1959) *interchange oscillation*
It corresponds to strict interchange of plasma elements.
The plasma elements oscillate back and forth across magnetic field lines, however, without perturbing their distribution.
In this simulation there are no node points⌂ in the directions perpendicular to magnetic field lines, nor in the direction parallel to ***B* (see the Introduction in the ReadMe.pdf file)**.

The black solid lines are dipole magnetic field lines. The white crosses correspond to positions of oscillating plasma elements; this animation shows their changing position as a function of time. At initial time the plasma elements are located along segments of magnetic field lines; their initial positions are permanently indicated by black dots fixed during the whole animation.

In the present animation (File_1.gif) the white crosses experience stationary oscillations in the direction transverse (perpendicular) to the magnetic field lines, but no motion parallel to the ***B***-field direction.

Although in this first animation the amplitude of the transverse displacement (: the input parameter #1) is not equal to zero ($A_\perp \neq 0$), the wave number (: the input parameter #2) in any direction perpendicular to ***B*** is equal to zero : $k_\perp = 0$.
NB: in this simulation, as well as in all other ones, the motion of the plasma elements remains always parallel to the meridian plane: i.e. it has no component in the direction perpendicular to the meridian plane ¤.

In the interchange oscillation illustrated in this first simulation $A_{//}$, the field aligned amplitude (: the input parameter #3) of the wave, and $k_{//}$, the parallel wave number (: the input parameter #4), are both set equal to zero §.

⌂ Node points are points where the plasma elements do not move (their displacement is zero).
Their number in a particular direction is equal to twice the component of k, the wave vector in that direction.

¤ Assuming that $A_\varphi = 0$ implies that the interchange motion has no azimuthally oriented component. This will also be assumed in any of the animations presented below. However, this restriction is not essential. It has been adopted for simplification in our 2D simulation. Of course, this limitation could easily be relaxed in other versions of our IDL code. Future versions of this code could be developed to illustrate interchange oscillations for which the amplitude (A_φ) and the wave number (k_φ) would not equal to zero, as assumed here. Poloidal modes of interchange oscillations exist also in the magnetosphere, but have not been considered in our set of animations. Note that they had not been envisaged, neither in the paper of Gold (1959), nor in most other studies of magnetospheric interchange. To simulate such more general modes more sophisticated 3D animations would have to be developed.

§ The mode of oscillation illustrated in this first animation corresponds to what Newcomb (1961) has been called "pure-interchange" (P-I) modes. He considered the "pure interchange mode" as the asymptotic limit of the "Type 1 Quasi-Interchange modes" when $k_{//} \Rightarrow 0$.

Following Newcomb's original nomenclature, we call *Pure-Interchange* (P-I) this interchange mode for which $k_{//} = 0$. This implies that P-I modes have no node points along magnetic field lines.

Note that these restrictive assumptions and limitations are relaxed in the animations #3, #4 and #5, where Quasi-Interchange (Q-I) motions are illustrated.

The period of oscillation (: the input parameter #5) and phase angle (: the input parameter #6) are assumed to be independent of the positions of the plasma elements. Of course, these simplifying assumptions can also be relaxed in future versions, but this would be at the expenses of a higher degree of sophistication of this code and an increased but unnecessary mingling of the displays.

In the present P-I animation, all plasma elements move from on segment of the background dipole magnetic field lines distribution to another; all plasma remaining co-aligned with background field lines. This ad-hoc assumption has been endorsed in most studies of magnetospheric interchange for over two decades [#]. Indeed, under such conditions all plasma elements move synchronously in the meridian plane from one dipole field line to another one, and as a matter of consequence magnetic field lines of the system are not bent (perturbed) by the transverse oscillations of the plasma elements [%].

[#] This is a postulate on which the ideal MHD approximation is based in plasma physics. Indeed, according to this assumption magnetic field lines are electrical equipotential lines: parallel electric fields are assumed to null ($\boldsymbol{E}.\boldsymbol{B} = 0$) **.** Strictly speaking Alfvén's frozen-in-field theorem is applicable only under this restrictive condition. This was the dominant paradigm in magnetospheric physics in the 60's and has remained so for over three decades. The drift velocities of plasma elements was then exclusively determined by $\boldsymbol{u} = \boldsymbol{E} \times \boldsymbol{B} / B^2$; the displacements of plasma elements (and of the frozen-in field lines) were essentially perpendicular to the magnetic field lines. This ideal MHD assumption was introduced in the theory of magnetospheric interchange by Gold (1959). It was adopted by Dungey (1961) in his well known paper on reconnection, and henceforth used in all subsequent theories of interchange until the end of the 80's (e.g. Southwood and Kivelson, 1989). In spite of the seminal article of Newcomb (1961) and others, the ideal MHD postulate has remained deeply anchored in many domains of theoretical plasma physics. Eventually, it has been almost forsaken, when alternative, less restrictive (non-ideal MHD and kinetic) approximations of plasma physics have become more popular and (re)considered by Ferrière and Andre (2003) and Andre (2003) to describe interchange and quasi-interchange motions of plasma elements.

[%] The absence of bending of the background magnetic field line distribution implies that the magnetic field lines are electric equipotentials ($\boldsymbol{E}.\boldsymbol{B} = 0$) and that the drift velocity of the plasma is perpendicular to B and determined by $\boldsymbol{u} = \boldsymbol{E} \times \boldsymbol{B} / B$. This is the well known postulate made in the ideal MHD approximation of plasma physics. It is nowadays considered, however, that this ideal approximation is rather restrictive. Indeed it is now becoming accepted that most of the time the geomagnetic field lines are not electric equipotential lines, and that the frozen-in field condition, $\boldsymbol{E}.\boldsymbol{B} = 0$, is often violated in the magnetosphere and astrophysical plasmas (e.g. of course in the case of electromagnetic waves propagating into the magnetosphere, but even in case of ULF and Alfvén waves where the electric field intensity has a non-zero parallel component).

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2. File#2 (File_2.gif) illustrates an animation of a *pure-interchange mode* which is convectively unstable. This case corresponds to a steady state expansion of plasma elements in the direction transverse to the magnetic field lines.

This animation is similar to the previous one (File_1.gif), except that the "oscillation frequency" has now an imaginary value, changing the periodic oscillation into a steady state expansion of the plasma elements in directions perpendicular to the magnetic field lines. As above this ideal MHD plasma motion has no azimuthally directed convection velocity component.

This run corresponds to an unstable *P-I mode* indeed there are no displacements of the white crosses in the direction parallel to the magnetic field lines ($k_{//} = 0; A_{//} = 0$).

The expansion rate in this animation is stationary (i.e. independent of time). Non-uniform expansion rates can easily be implemented in more sophisticated versions of the IDL code developed to display these animations.

In the next set of animations we will abandon *pure -interchange modes and* illustrate *Quasi-Interchange (Q-I) modes* for which $k_{//} \neq 0$.

3. File#3 (File_3.gif) illustrates an animation of *type 1 Quasi-Interchange mode (also called transverse mode).*

In this Quasi-Interchange (Q-I) mode the white crosses (which were initially aligned with background magnetic field lines) oscillate periodically about their initial positions. Their oscillation has components both transverse and parallel to the local magnetic field direction (but not perpendicular to the meridian plane).

Unlike in the two previous animations, the stationary oscillations have now a component parallel to ***B***. The amplitude ($A_{//}$) of these field aligned displacements and the wave number ($k_{//}$) parallel to magnetic field lines are both different from zero.

Since $k_{//} \neq 0$ there is a finite number of node points along magnetic field lines. Furthermore, since $k_{\perp} \neq 0$, there are a number of magnetic field lines for which all points are node points, i.e. where the plasma elements are at rest.

The *type 1* mode of Q-I oscillation illustrated here has a significantly larger amplitude ($A_{\perp}$) in the direction perpendicular to ***B*** then in the direction parallel to the field lines. Since $A_{\perp} >> A_{//} \neq 0$, this type 1 quasi-interchange mode will be called the *transverse Q-I mode.*

Note that in the limit $k_{//} \Rightarrow 0$, the *strict interchange modes* of Gold (1959) and the generalized interchange modes of Southwood and Kivelson (1987) are recovered[§]. Note that the pure interchange limit is also recovered in our simulations when $A_{//} \Rightarrow 0$.

The next animation illustrates a *Q-I oscillation of type 2* where $A_{//} >> A_{\perp} \neq 0$.

[§] Let's emphasize that in all our animations presented here, magnetic field lines (the black lines) are virtual lines: i.e. mathematical lines that are everywhere tangent to the local magnetic field directions. The "motion of magnetic field lines" cannot be measured with any existing physical instrument. Therefore we avoid to say that these lines move. However, this does not mean that the distribution of the magnetic field lines is not perturbed or bent by the motion of the plasma elements. The changes of magnetic field lines due to the motion of the plasma are not displayed in our animations.

These B-field perturbations are small when β, the ratio of the thermal energy density over the magnetic energy density, is much smaller than unity. Indeed, under such conditions the electric current densities associated with the interchange motion of the electrons and ions are small, and consequently the magnetic field perturbations are also small compared to the background ***B***-field.

The values of β are much smaller than 1 in the inner magnetosphere where the plasma is cold. Under these circumstances it may be consider that the shape of magnetic field lines is not significantly affected (bent) by the diamagnetic current density distribution generated by motion of diamagnetic plasma elements.

However, when and where $\beta > 0.1$, as for instance close to the magnetopause, the periodic oscillation of the plasma elements due to Q-I interchange will generate large diamagnetic field perturbations. The background magnetic field distribution (due to distance electric currents or magnets) will then be significantly perturbed, and the virtual magnetic field lines will then appear to be time-dependent, i.e. not fixed as assumed in our simulations. Under such conditions (i.e. in the case of high β plasmas) magnetic field lines will change (will appear to oscillate, or drift) with the same frequency as the plasma elements, but not with the same amplitude as generally considered in ideal MHD theories of interchange motion when magnetic field lines are assumed to be completely frozen-in the plasma.

Interchange motion implies that plasma streamlines are not closed as usually assumed in the plasmasphere when invoking the ideal MHD approximation, and, therefore, cold plasma elements are slowly drifting outward from the inner plasmasphere to the plasmapause along winding up spiral drift paths as considered in our simulations.

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4. File#4 (File_4.gif) illustrates an animation of *type 2 Quasi-Interchange mode (translational mode).*

For the *type 2 Q-I mode* the amplitude of plasma displacements along magnetic field lines is larger than the amplitude of the displacement transverse to ***B***: i.e. $A_{//} >> A_{\perp} \neq 0$.

The perpendicular and parallel wave numbers can take any real (or complex) values. In the limit $A_{\perp} \Rightarrow 0$ field aligned flow regimes are obtained (field aligned oscillations); furthermore, when $A_{\perp} = 0$ and $k_{//} = 0$, stationary inter-hemispheric plasma flows across the equatorial plane can be simulated.

For plasma elements whose temperature exceeds a few hundred °K, the instability Q-I modes is triggered when the curvature of the magnetic field lines becomes larger than certain critical thresholds. André and Lemaire (2006) showed that the magnetic tension resulting from the curvature of geomagnetic field lines is large enough to drive the thermal plasma unstable deep inside the plasmasphere.

André and Lemaire (2006) have shown also that the *type 2 Q-I modes* become unstable before the *type 1 Q-I mode* does: i.e. the *type 2 mode* is more prompt to become unstable than the *type 1 mode.*

They infer that it is the *type 2 Q-I* instability that drives Lemaire-Schunk *Plasmaspheric Wind* inside the plasmasphere (Lemaire and Schunk, 1992, 1994).

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5. File#5 (File_5.gif) illustrates an animation of the *Plasmaspheric wind.*

In this final simulation we illustrate a combination of field-aligned upward plasma flow and transverse Q-I flow. The transverse velocity is maximum in the equatorial region and small at higher latitudes. This animation simulates the plasmaspheric wind flow inside the inner magnetosphere.

The plasmaspheric wind has both velocity components parallel and perpendicular to the distribution of magnetic field lines, just like in this animation. This combined field aligned and transverse plasma flows is expected when *type 2 Q-I* modes become convectively unstable.

This continuous expansion of the plasmasphere was first suggested by Lemaire and Schunk (1992, 1994), based on equatorial ion density profiles observed by OGO5. Recently André and Lemaire (2006) have identified the origin of this continuous expansion of the plasmasphere.

They conclude that the magnetic tension resulting from the curvature of geomagnetic field lines is the driver of Lemaire-Schunk's Plasmaspheric wind. Experimental evidence for the existence of a plasmaspheric wind has been found in recent RPI observations from IMAGE and CIS observations from CLUSTER.
