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Convective instabilities in the plasmasphere

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Abstract

According to observations, the averaged slope of the equatorial plasma density distribution is nearly constant ($\mathrm{d}\ \ln n/\mathrm{d}L = -0.724$) during very quiet geomagnetic activity from $L = 2$ to $L > 7$, and even smaller ($\mathrm{d}\ \ln n/\mathrm{d}L = -1.5$) during more typical quiet activity. These slopes are steeper than the threshold values for which magnetostatic plasma density distributions in the equatorial regions become unstable with respect to transverse and translational interchange motion in the Earth's gravitational and magnetic fields. When the effects of a centrifugal force due to corotation of the plasma with the angular velocity of the Earth are taken into account, these convective instability thresholds are significantly affected, at least in the vicinity of and beyond geosynchronous orbit. Nevertheless, for $L < 6.6$, neither instability criterion is satisfied (i.e. corotating plasma should be convectively stable inside geosynchronous orbit) for the observed density slope as well as for that corresponding to a rigidly corotating plasmasphere in magnetostatic equilibrium. This conclusion holds under the assumption that the unperturbed magnetic field lines are straight (i.e. not curved, as are geomagnetic field lines). However, this assumption is not realistic and the effects associated with the magnetic curvature are largely dominant over the effects of the effective gravity in the equatorial regions of the plasmasphere and of the magnetosphere in general. When the effect of magnetic field tension (due to the curvature of the dipole magnetic field lines, and B-field gradient) is properly taken into account, the thermal plasma confined in the Earth's dipole magnetic field cannot remain in magnetostatic equilibrium but becomes convectively unstable for smaller L, i.e. much deeper inside the equatorial plasmasphere. In other words, the equatorial region of the plasmasphere becomes convectively unstable at much lower altitudes when the curvature of dipole magnetic field lines is taken into account. Thus the existence of a plasmaspheric wind is supported by our theoretical result: i.e. the equatorial plasmasphere is not in magnetostatic/barometric/diffusive equilibrium, but is convectively unstable at $L = 2$ and beyond. The picture of a static equatorial plasmasphere seems to be at odd, even in a saturated stage following a long period of quiet geomagnetic conditions.

Keywords: Magnetosphere; Plasmasphere; Instabilities; Interchange

1. Introduction

The dynamics of the terrestrial magnetosphere is mainly powered by its interaction with the variable incident solar wind. The plasmasphere is known to be globally sensitive to geomagnetic disturbances and activity induced by this interaction, and in

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particular to the substorms growth/recovery cycle associated with disturbed and quiet geomagnetic periods (Corcuff et al., 1972; Park, 1973, 1974a,b). This dependence is illustrated by the change of the equatorial distance of the plasmapause versus magnetic activity index, K_p, which happens to be a useful proxy to infer the state and size of the plasmasphere. It has been noticed that during periods of extended quiet geomagnetic activity (low values of K_p) the geosynchronous orbit is located inside the plasmasphere, whereas during geomagnetically active periods (high values of K_p) the plasmapause is found closer to the Earth, and consequently the geosynchronous orbit lies outside the plasmasphere. During the latter periods, the plasmasphere is eroded (in a state of depletion), whereas during the former periods it is filled with plasma of ionospheric origin (in a state of refilling). The present article is precisely concerned with the description of the plasmasphere during extended quiet geomagnetic periods following a substorm, i.e. not during the sporadic or intermittent formation of a new plasmapause.

Lemaire and Schunk (1992, 1994) suggest the presence of continual losses of plasma from the plasmasphere, a plasmaspheric wind, driven by interchange plasma motions. They postulate the existence of a slow and permanent cross-B transport of plasma from the inner to the outer regions of the plasmasphere, even during prolonged periods of quiet geomagnetic conditions when substorms disturbances are absent. Such a radial transport implies that plasma streamlines are not closed, and consequently that cold plasma elements slowly drift outward from the inner plasmasphere to the plasmapause along winding up spiral drift paths.

Motivated by recent discussions both on the existence of such a plasmaspheric wind (Lemaire, 1999, 2001) and on the stability criterion of the interchange instability (Ferrière and André, 2003), we aim at testing these theoretical local stability criteria against several models of plasma and field distributions in the plasmasphere. We wish to investigate whether or not these profiles are unstable, and discuss Lemaire and Schunk's (1992, 1994) plasmaspheric wind concept.

Our paper is divided as follows: In Section 2, we present the different models of the plasmasphere available. In Section 3, we briefly summarize the qualitative arguments in favor of the existence of a plasmaspheric wind. In Section 4, we discuss the stability criteria of quasi-interchange modes, introducing in particular the effects of the magnetic curvature. In Section 5, we test the local stability of the quasi-interchange modes against several models of the plasma and field distributions in the plasmasphere. In Section 6, we summarize our study.

2. Plasmasphere modeling

Two extreme types of magnetostatic equilibrium distributions are commonly used in order to model the plasmaspheric densities and temperatures along magnetic field lines, and to determine their radial profile in the equatorial plane of the magnetosphere. The two types of distributions are the exospheric equilibrium distribution and the diffusive equilibrium distribution. Both types are controlled by the effective gravitational (including the centrifugal forces) and electrical potential distributions. The electrical potential arises from the parallel electric field required to maintain the quasi-neutrality of the plasma. This ambipolar electric field has been discussed first in the astrophysical context by Pannekoek (1922) and Rosseland (1924), and by Lemaire and Scherer (1974) in the magnetospheric and solar wind context.

Particles moving along a magnetic field line in the effective gravitational and electrical potential fields can be organized according to the different classes of their orbits. The orbits depend on their kinetic energy and pitch angle. Three classes of orbits are identified, corresponding to ballistic, escaping and trapped particles. Ballistic particles originate from one ionospheric hemisphere and have not enough energy to reach the magnetic equatorial plane, as a matter of consequence they fall back into their region of origin. Escaping particles originate from one ionospheric hemisphere and may reach the conjugate hemisphere where they are scattered by collisions. Trapped particles bounce along the magnetic field line between reflection/mirror points (due to restoring forces of magnetic or non-electromagnetic origin) located in the ion-exosphere, beyond the collision-dominated regions of the ionosphere.

The exospheric and diffusive equilibrium distributions differ by the relative population rate of these different classes of orbits. In what follows, each of these theoretical distributions will be considered to characterize the different states of the plasmasphere.

2.1. Exospheric equilibrium model

In magnetostatic exospheric models, the field-aligned plasma distribution is formed only of ballistic and escaping particles, and the trapped orbits are totally depleted. Consequently, the pitch angle distribution is strongly field-aligned, cigarlike, and highly anisotropic for escaping particles. Such collisionless models have been developed in the past for Maxwellian (Lemaire, 1976) or Lorentzian (Pierrard and Lemaire, 1996) particle velocity distribution functions.

Interestingly enough, the exospheric density distribution can be considered to represent an almost depleted magnetic flux tube, soon after a magnetic storm has eroded the plasmasphere. Lemaire (1989) proposed therefore a kinetic refilling scenario where ionospheric ballistic and escaping particles invade first an empty flux tube in less than 4 h and build up a density distribution corresponding to a minimum exospheric equilibrium. The increase of flux tube content and of the collision rate later on allow for trapped particle orbits to become gradually and continuously populated by pitch angle scattering.

The validity of this scenario is supported by plasma data from the GEOS-2 geosynchronous satellite (Sojka and Wrenn, 1985). During the first two days of prolonged quiet geomagnetic conditions, the GEOS-2 observations indicate that the refilling rate of geosynchronous flux tubes is high and the cold plasma distribution field-aligned, whereas the refilling rate becomes lower and the cold plasma distribution more isotropic after this initial phase.

2.2. Diffusive equilibrium model

In the case of hydrostatic and isothermal diffusive equilibrium models, the velocity distribution of particles is an isotropic and isothermal Maxwellian or Lorentzian distribution function for all classes of orbits. The resulting field-aligned density distribution decreases exponentially or as a power law, as a function of the effective gravitational and electric potential energy of the particles.

The diffusive density distribution is usually adopted to model plasma distribution along field lines located well inside the plasmasphere and is often considered to represent an advanced or saturated state of refilling flux tube, during a period of long lasting quiet geomagnetic conditions. Such a distribution has been widely used in the past to infer the equatorial density from whistler spectrograms (Angerami and Carpenter, 1966; Park, 1974a,b).

However, the diffusive equilibrium model discussed here corresponds to an idealized situation, particularly not well-suited to model the density distribution at large distances in the plasmasphere, in the sense that prolonged period of very quiet geomagnetic conditions are very rare (although they occur from time to time). Consequently, the farthest plasmaspheric flux tubes should not have enough time to refill and reach a diffusive equilibrium with the ionosphere before it is depleted again at the onset of the next substorm. The density distribution in the outer regions of the plasmasphere is more likely intermediate between the exospheric and diffusive distributions (Pierrard and Lemaire, 2001).

We are aware that both the hydrostatic diffusive and exospheric models are oversimplified models, since they assume the plasma distribution to be stationary, i.e. time independent and with no net mass flow along the magnetic field line, whereas for example asymmetries in the field line geometry and in the boundary conditions at the feet of the flux tubes are expected to lead to interhemispheric plasma flows. Nevertheless, these oversimplified models represent two extreme situations and will be considered in our application. More sophisticated dynamical models with interhemispheric ionization flows could be envisaged in future studies and refinements, but this should not jeopardize the conclusions obtained below using these simplified hydrostatic models.

2.3. Empirical model

An empirical model of equatorial electron density distribution in the plasmasphere under prolonged unperturbed geomagnetic activity condition has been determined by Carpenter and Anderson (1992). Their well-known model covers the radial distance range $2.25 < L = R/R_e < 8$ and is based on the use of two complementary electron density data sets, derived from the sweep frequency receiver onboard ISEE 1 and from ground-based whistler measurements. The comparison between in situ measurements and whistler probing technique (Carpenter et al., 1981) can be shown to be in good agreement with the Carpenter and Anderson (1992) model.

The Carpenter and Anderson empirical model of plasmaspheric equatorial densities indicates that after prolonged periods of very quiet geomagnetic activity the equatorial densities in the plasmasphere reach a saturation level and decrease exponentially with radial distance. The slope of the logarithmic equatorial density (n in cm^{-3}) profile is independent of L, and $d \ln n/dL$ equals to -0.724. Occasionally, during quiet geomagnetic activity, this slope has been observed to be even steeper (between -1.2 and -1.8), but associated with a less extended and saturated plasmasphere (Gallagher et al., 2000; Smilauer et al., 2002; Huang et al., 2004; Reinisch et al., 2004). We will mainly refer to the Carpenter and Anderson model in the applications presented below, but will not overlook the cases of even steeper plasmaspheric equatorial density gradients.

Recently, Pierrard and Lemaire (2001) have shown that it is possible to recover the Anderson and Carpenter empirical distribution by adding to an exospheric equilibrium model an unsaturated and L-dependent fraction η of trapped particles. Close to the planet, the required fraction to give the best fit to observed equatorial densities is close to $\eta = 1$ since trapped orbits are nearly saturated, whereas at large distances the required fraction becomes very small ($\eta \ll 1$). This η-exospheric model will also be used in the applications presented below.

3. Existence of a plasmaspheric wind

Noting the systematic differences between theoretical hydrostatic models and the observed density distribution in the plasmasphere, Lemaire and Schunk (1992) propose the conceptual existence of a continuous plasmaspheric wind transporting plasma of ionospheric origin across closed geomagnetic field lines, similar to that of the subsonic expansion of the equatorial solar corona. We briefly recall the different arguments presented by Lemaire and Schunk (1992) supporting a plasmaspheric wind.

Lemaire and Schunk (1992) simulated first the motion of plasma elements in the plasmasphere associated with the electric drift velocity, by using McIlwain (1986) magnetospheric electric field model. Since their model electric and magnetic field distributions were not dependent on time, the convection drift paths of the considered plasma elements are ideally closed curves.

Considering then a simple refilling scenario, with an ionization flux varying with time as the equatorial density increases, Lemaire and Schunk (1992) estimated the equatorial densities in drifting and refilling flux tubes, and noted that a flux tube located at $L = 4$ would take only 2.5 days to completely refill and reach a state of diffusive equilibrium.

However, the refilling time deduced from whistler observations by Park (1970) is much longer than 2–3 days. Even after 8 days of quiet conditions a flux tube at $L = 4$ is still refilling. Tarcsai (1985) reported that the day to day filling of the plasmasphere after magnetic disturbances continues through several days without exhibiting saturation levels corresponding to diffusive equilibrium, even for L distances deep inside the plasmasphere. Some more recent observations found refilling time of less than 28 h around $L = 2.5$ (Reinisch et al., 2004), but still insufficient to reach saturation levels.

This discrepancy could be resolved if in addition to corotation-convection equatorial plasma elements have an outward velocity. As noted by the authors, it will take more time to refill a flux tube when the plasma leaks out by moving parallel to the equatorial plane (as consequence of cross-B quasi-interchange motion of type 1, see below for a definition). The refilling time is then longer than the time required for a flux tube to reach diffusive equilibrium when it circulates continuously along the same closed drift path without any sort of quasi-interchange motion. In a steady-state situation, what flows up into the plasmasphere from the dayside ionosphere is balanced by what flows back down into the nightside ionosphere.

Titheridge (1976) examined the transition altitudes where the protons density is larger than the oxygen ion density. He found altitudes higher than the altitude where chemical equilibrium prevails at all local times. This implies upward protons flux at all local times for $L > 1.7$–2 and this led Lemaire and Schunk (1992) to conclude again that a continuous upflow has to be balanced by a continuous leakage of plasma flow across geomagnetic field lines in the equatorial region.

Under quiet geomagnetic conditions, the observed rate of increase in daytime flux tube content is larger than the downward flux required to maintain the nocturnal ionosphere (Park, 1970). Consequently, there are more ions flowing from the ionosphere into the plasmasphere during the day than returning to the ionosphere during the night. The net filling never stops in the inner plasmasphere and thus a continuous source of plasma is provided to the equatorial regions. Since the plasma cannot theoretically accumulate indefinitely, it has to be transported outwards. Since the substorm induced peeling off the plasmasphere does not operate at small radial distances, it is more likely that the plasmaspheric wind proposed by Lemaire and Schunk (1992) constitutes the required loss mechanism.

Further arguments supporting the existence of a plasmaspheric wind can be derived from the observed equatorial densities and from their radial gradient in the plasmasphere. The values of the equatorial densities inferred by Lemaire and Schunk (1992) with their simple simulations are generally larger than the observed values (Chappell et al., 1970) by a factor of 3 or 4. When the concept of a plasmaspheric wind with a uniform outward velocity is taken into account, the equatorial density distribution of such an expanding plasmasphere (with a small refilling rate compared to its expansion rate) varies as L^{-4}. Such a characteristic profile has often been reported in the outer plasmasphere (Chappell et al., 1970) from OGO-5 observations. Deviations from this characteristic profile can moreover give us some indications on the contribution and importance of the refilling rate or on the non-uniformity of the expansion velocity.

Finally, after many days of very quiet geomagnetic conditions, there is no evidence of a sharply defined plasmapause, contrary to what could be expected from the Last Closed Equipotential scenario, where a well-developed knee should exist along the last closed streamline of the magnetospheric convection electric field after over 24 h of stationary magnetospheric convection. There is no observational reason to assume that the streamlines of plasma elements inside the plasmasphere are truly closed curves, and it is more likely that they consist of open spirals if the plasmasphere is expanding slowly.

From a theoretical point of view, the presence of a plasmaspheric wind has been considered to result from a plasma interchange motion driven by an imbalance between gravitational, centrifugal, and pressure gradient forces. However, the presence of stratification of the plasmaspheric pressure distribution and of non-electromagnetic forces leads to the destabilizing of a broader category of modes driven by buoyancy forces, known as quasi-interchange modes, that trigger transverse as well as translational plasma motions. In the next section, we give a general description of these modes and in particular of their stability criteria, before their application to realistic plasmaspheric profiles.

4. Quasi-interchange modes

Interchange motions have been extensively discussed in the literature under a variety of simplifying assumptions sometimes unrealistic and unproven. A review of this abundant literature can be found in the introductory section of Ferrière et al. (1999).

Gold (1959) was the first to introduce the concept of interchange of magnetic flux tubes in the magnetospheric context. Its so-called strict interchange model assumes a one to one interchange between magnetic flux tubes enclosing the same magnetic flux and thus leaving the shape of the magnetic field lines unchanged as well as the magnetic energy of the system unperturbed. Cheng (1985) pointed out much later that this model is at odd with the requirement of total pressure balance, and that a realistic flux tube interchange must be accompanied by a change in field magnitude. The so-called generalized interchange model of Southwood and Kivelson (1987) still assumes that the interchanging flux tubes preserve everywhere the direction of the local magnetic field, but they relax the condition that the energy density of the magnetic field is unperturbed by the interchange. Both models are in fact unphysical, insofar as true interchange motions of plasma elements generally entail also distortions of the distribution of magnetic field lines preserving the equilibrium of total pressure (plasma plus magnetic pressure).

Newcomb (1961) studied the influence of the gravitational field and of stratification on the three modes of the ideal magnetohydrodynamic (the Alfvén mode, the fast and slow modes). He considered a plasma confined in a horizontal magnetic field distribution by a uniform vertical gravitational field. Newcomb (1961) identified two convective wave modes whose dispersion relation $\omega = \omega(\mathbf{k})$ is influenced by the stratification of the plasma in the vertical direction, for nearly perpendicular wave vector. These two modes can be distinguished by their behavior in the limit of zero parallel wave vector: $k_{\parallel} \to 0$. In this limit the convective wave modes fall into two types and were given the name of quasi-interchange modes.

The quasi-interchange modes have been studied more comprehensively than earlier by Ferrière et al. (1999) for the case of collisional plasmas, and by Ferrière and André (2003) for the case of collisionless proton–electron plasmas, by taking into account both the effect of the gravitation and the effect of magnetic field line curvature. The stability criteria of all quasi-interchange modes have been derived and tested versus a distribution of plasma and magnetic field in the Io torus (André and Ferrière, 2004).

We stick to Newcomb's original terminology (types 1 and 2 quasi-interchange modes, although for mnemotechnical reasons we will also call Newcomb's type 1 mode the transverse interchange mode, while we will use translational interchange mode for Newcomb's type 2 quasi-interchange mode). Let us first describe the two types of quasi-interchange modes in the following section. The problem of their stability will be addressed next.

4.1. *Type 1 quasi-interchange mode* (*transverse interchange mode*)

In the limit $k_{\|} \rightarrow 0$, i.e. when the parallel component of the wave vector tends to zero, the type 1 mode corresponds to Gold's pure interchange mode. The plasma motion is then essentially perpendicular to the unperturbed curved magnetic field lines.

The quasi-interchange mode is then driven by the buoyancy force, i.e., a sum of (i) the gravitational buoyancy force, arising from density inhomogeneities in the gravitational field, and (ii) the magnetic buoyancy force, arising from magnetic tension in a curved magnetic field line distribution. As illustrated in Fig. 1, the type 1 quasi-interchange mode can be unstable and lead to cross-B plasma transport. This is why we label it here also transverse quasi-interchange mode.

The counterpart of the type 1 mode in hydrodynamics is the classical Rayleigh–Taylor instability, where fluid elements exchange their position under the action of the gravitational force, the lighter one lying in a stable configuration on top of the heavier one. In the magnetospheric context, under the action of the only centrifugal forces and beyond the geostationary orbit for example, plasma elements with an excess density tend to exchange position with plasma elements of lower density located further away from the axis of rotation.

4.2. *Type 2 quasi-interchange mode* (*translational interchange mode*)

The type 2 quasi-interchange mode corresponds to a pure translational mode in the limit of zero parallel wave vector ($k_{\|} \rightarrow 0$), i.e., the plasma motion is mainly along the unperturbed magnetic field lines.

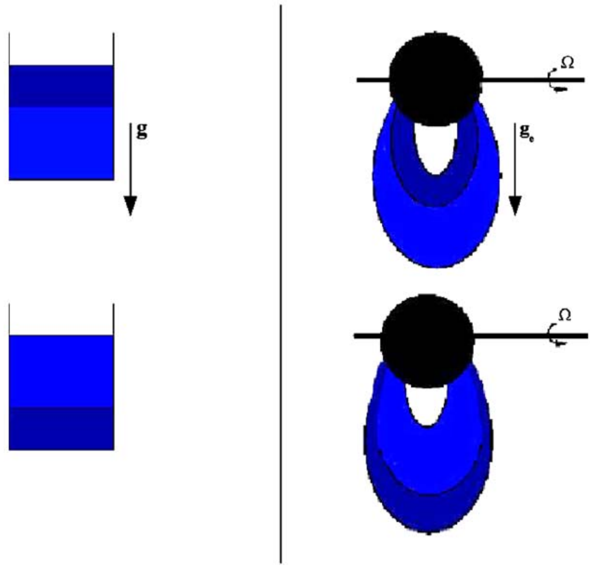

Fig. 1. Type 1 mode: analogy between the hydrodynamic picture and the magnetospheric context. Left: a denser fluid (in dark blue) exchanges its position with a lighter one (in pale blue) under the action of the gravity $\vec{g}$. Right: a plasma element with an excess density (in dark blue) exchanges its position with an element of lower density (in pale blue) under the action of the effective gravity $\vec{g}_e$ including the effect of the centrifugal forces due to the planetary rotation Ω.

This mode is driven by the projection onto the perturbed field lines of the thermal pressure gradient and gravitational plus centrifugal forces as illustrated in Fig. 2. It pertains to the class of ballooning modes although there exists no clear consensus on the exact definition of the ballooning modes. It is usually considered as a localized low-frequency perturbation driven unstable by a thermal pressure gradient in a magnetic field line distribution with unfavorable curvature, causing unstable plasma elements to bulge out at weak spots as illustrated in Fig. 2 (Ferrière et al., 1999). Liu (1997) identified for example the ballooning mode with the less stable quasi-interchange modes, thereby being either the type 1 mode or the type 2 mode depending on the plasma parameters considered.

The counterpart of the type 2 mode in hydrodynamics is given by the displacement of a fluid in the direction of the gravitational force when the fluid elements tend to migrate toward a point of minimum potential energy. In the magnetospheric context, plasma elements are displaced in the

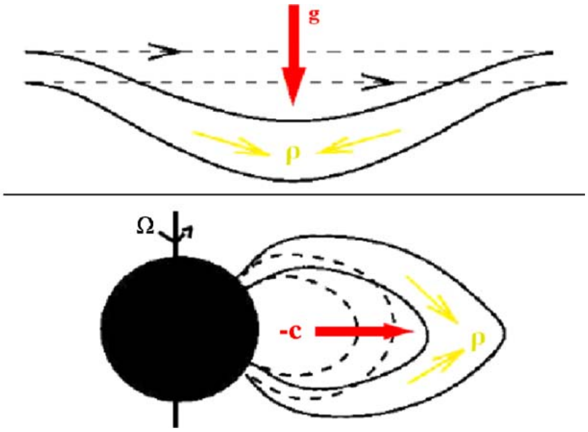

Fig. 2. Type 2 mode: analogy between the hydrodynamic picture and the magnetospheric context. Top panel: a downward motion (in the direction of the gravity $\vec{g}$) of a water pipe is accompanied by a converging flow of water inside the pipe (as indicated by yellow arrows). Bottom panel: an outward displacement (opposed to the direction of the magnetic curvature vector $\vec{c}$) of a flux tube is accompanied by a parallel convergence of plasma along field lines (as indicated by yellow arrows).

direction of the gravity and fall toward the equatorial plane.

4.3. Stability criteria for a collisional isotropic plasma

We will first consider the simplest case of a collisional isotropic plasma in static equilibrium. The more general case of a collisionless plasma with anisotropic pitch angle distributions will be considered next. To derive the stability criteria of quasi-interchange modes as André (2003) we explicitly take into account the effects of non-electromagnetic forces (through an effective gravitational acceleration including a centrifugal component) and the curvature of magnetic field lines. We take also into account the stratification of the plasma in magnetostatic equilibrium (including gradients of the equilibrium parameters). All the stability criteria are derived through a local linear expansion of the perturbed plasma state. A set of restrictive assumptions are also imposed to make the dispersion relation tractable. Perturbations are assumed to have a wavelength much shorter than the equilibrium density scale height; furthermore, the equilibrium parameters are assumed to be uniform along the curved magnetic field lines. For convenience, we assume also that the vector of effective gravity is parallel to $\vec{c}_0$ the magnetic curvature vector, a situation only achieved in realistic dipolar configurations close to the equatorial plane, and we neglected Coriolis forces. Ferrière et al. (1999) have shown that in that case one and only one quasi-interchange mode (either the transverse one or the translational one) can be unstable.

The main reason to start with the case of a collisional isotropic plasma is to outline the effects of magnetic curvature generally neglected or underestimated in earlier studies. Lemaire (1999, 2001) investigated the stability of the quasi-interchange modes in an isothermal plasmasphere in diffusive equilibrium, but did not consider the effects of the magnetic field curvature. However, it will be shown below that the curvature term is indeed dominant in the magnetospheric context, at least when the temperature of the plasma is not set equal to zero as in cold plasma approximations.

4.3.1. Gravity only

When the equilibrium magnetic field lines are straight (i.e., with no magnetic field curvature, i.e. $\vec{c}_0 = \vec{0}$), the overall stability criterion for all quasi-interchange modes (types 1 and 2 together) reads

$$\vec{g} \cdot \left(\frac{\vec{\nabla}\rho_0}{\rho_0} - \frac{\vec{g}}{C_s^2} \right) \geqslant 0, \tag{1}$$

where $\vec{g}$ is the effective gravity (including the effects of the centrifugal forces); ρ_0 is the plasma density at equilibrium (subscript 0), and $C_s^2 = (\gamma P_0/\rho_0)$ is the sound speed squared, with P_0 the total kinetic pressure of the plasma (i.e. the sum of the electron and ion pressures) assumed to be isotropic, and γ the adiabatic index.

The stability criterion for the type 1 quasi-interchange mode (transverse interchange mode) alone is given by the more stringent condition

$$\vec{g} \cdot \left(\frac{\vec{\nabla}\rho_0}{\rho_0} - \frac{\vec{g}}{V_A^2 + C_s^2} \right) \geqslant 0, \tag{2}$$

where $V_A^2 = (B_0^2/\rho_0\mu_0)$ is the Alfvén speed squared.

The stability criterion (1) for all quasi-interchange modes does not depend on the value of the magnetic field intensity B_0. Consequently, the magnetic field does not play any stabilizing nor destabilizing role on the type 2 quasi-interchange mode, whereas it does for the type 1 quasi-interchange mode. Indeed, the stability criterion (2) depends on the value of the magnetic field through the Alfvén speed. Thus, the type 1 quasi-interchange mode (transverse mode) appears less easily driven unstable than the type 2 quasi-interchange mode (translational mode). Note that if the plasma density would be uniform in the plasmasphere (i.e. $\vec{\nabla}\rho_0 = \vec{0}$), both stability criteria would be violated everywhere in the plasmasphere.

These criteria are based on the assumption that the unperturbed plasma distribution is in magnetostatic equilibrium under the influence of a uniform gravitational field,

$$\vec{g} = \frac{\vec{\nabla}(P_{M0} + P_0)}{\rho_0},$$

where P_{M0} is the magnetic pressure ($B^2/2\mu_0$) at equilibrium.

Since the value of the effective gravity is determined by the mass of the central planet and rotation rate of the ionosphere, i.e., independent of the distributions of the plasma and magnetic field, the thermal pressure gradient does not influence the quasi-interchange stability, whereas the thermal pressure itself has a stabilizing effect (André and Ferrière, 2004). The direction of the effective gravity vector appears as an important factor governing the instability.

These stability criteria (1) and (2) correspond precisely to the criteria used by Lemaire (1999, 2001) in his investigation of the stability of a corotating isothermal plasmasphere against quasi-interchange modes. We will come back on these results in the next section, since he did not consider the curvature of magnetic field lines.

In the cold plasma approximation ($C_s^2 = 0$), the stability criterion of the type 1 quasi-interchange mode can be rewritten as

$$\vec{g} \cdot \vec{\nabla}\left(\frac{\rho_0}{B_0}\right) \geqslant 0.$$

When integrated along straight magnetic field lines it gives

$$\vec{g} \cdot \vec{\nabla}\eta \geqslant 0,$$

where $\eta = \int(\rho/B)\,\mathrm{d}s$ is the mass per unit magnetic flux, and one recovers the classical result of the interchange model originally introduced by Gold (1959). This is the stability criterion generally adopted in ideal magnetohydrodynamics for several decades in magnetospheric physics.

4.3.2. *Curvature only*

Let us now exclusively consider the effect of the curvature of magnetic field lines (without non-electromagnetic forces). When $\vec{g} = \mathbf{0}$ but $\vec{c}_0$ the curvature vector of the unperturbed magnetic field line is not equal to zero, the overall stability criterion for all quasi-interchange modes (types 1 and 2 together) reads

$$-\vec{c}_0 \cdot \frac{\vec{\nabla}P_0}{\rho_0} \geqslant 0, \tag{3}$$

whereas the stability criterion for type 1 quasi-interchange mode (transverse interchange mode) alone is rewritten as

$$-\vec{c}_0 \cdot \left(\frac{\vec{\nabla}P_0}{\rho_0} - \frac{2V_A^2 C_s^2}{V_A^2 + C_s^2}\,\vec{c}_0\right) \geqslant 0. \tag{4}$$

In the absence of gravitational and centrifugal forces, the magnetostatic equilibrium condition reads

$$V_A^2 \vec{c}_0 = \frac{\vec{\nabla}(P_{M0} + P_0)}{\rho_0}.$$

Again here, the stability criterion (3) for all quasi-interchange modes does not depend on B_0, the value of the magnetic field intensity. It is only the stability criterion (4) of the type 1 quasi-interchange mode (transverse mode) that depends on the value of the magnetic field through the Alfvén speed, V_A. Therefore, the magnetic field does not play any stabilizing or destabilizing role on type 2 quasi-interchange mode, whereas it does for type 1 quasi-interchange mode. The transverse interchange mode is less easily driven unstable than the translational mode; the later become unstable for smaller plasma pressure gradients than the transverse quasi-interchange mode, and consequently Gold's pure interchange is harder to drive unstable than the translational mode for which the plasma displacements are mainly parallel to magnetic field lines. The stability criterion for all quasi-interchange modes indicates that magnetic configurations with field lines that are concave toward regions of higher plasma pressure are indeed unstable.

The stability criterion for the transverse interchange mode can be rewritten in terms of the transverse gradient of the thermodynamic invariant $P_0 V_0^\gamma$ which is commonly used in the case of collisional plasmas. Taking into account the magnetostatic equilibrium condition and using the following geometrical relation:

$$\frac{\vec{\nabla}_\perp V_0}{V_0} = -\left(\frac{\vec{\nabla}_\perp B_0}{B_0} + \vec{c}_0\right),$$

where V_0 is the volume of a unit flux tube, criterion (4) becomes

$$-\vec{c}_0 \cdot \vec{\nabla}(P_0 V_0^{\gamma}) \geqslant 0,$$

which coincides with the pure interchange instability condition obtained by Southwood and Kivelson (1987) for $k_{\parallel} = 0$.

Since the magnetic curvature vector $\vec{c}_0$ is generally directed toward the planet, a collisional plasma would be stable against the transverse quasi-interchange motions if its thermal pressure decreases outward less rapidly than in an adiabatic distribution.

4.3.3. Combined effect of gravity and magnetic field line curvature

If one combines both the effects of gravity and curvature of magnetic field lines together, the stability criterion for all quasi-interchange modes (types 1 and 2 together) becomes

$$(\vec{g} - 2C_s^2\vec{c}_0) \cdot \frac{\vec{\nabla}\rho_0}{\rho_0} \geqslant 2C_s^2 \frac{\vec{\nabla}T_0}{T_0} \cdot \vec{c}_0 + \frac{\vec{g}}{C_s^2} \cdot (\vec{g} - 2C_s^2\vec{c}_0), \tag{5}$$

whereas the stability criterion for type 1 quasi-interchange mode (transverse interchange mode) alone becomes

$$(\vec{g} - 2C_s^2\vec{c}_0) \cdot \frac{\vec{\nabla}\rho_0}{\rho_0} \geqslant 2C_s^2 \frac{\vec{\nabla}T_0}{T_0} \cdot \vec{c}_0 + \frac{[\vec{g} + (V_A^2 - C_s^2)\vec{c}_0]^2}{V_A^2 + C_s^2} - (V_A^2 + C_s^2)\vec{c}_0 \cdot \vec{c}_0, \tag{6}$$

where T_0 is the plasma temperature at equilibrium (the electron and ion temperatures are assumed to be equal and isotropic due to frequent Coulomb collisions).

The plasma is again assumed to be initially in magnetostatic equilibrium such that

$$\vec{g} + V_A^2\vec{c}_0 = \frac{\vec{\nabla}(P_{M0} + P_0)}{\rho_0}.$$

It is more difficult to arrive to condensed stability criteria, except if we assume that the collisional plasma is isothermal ($\vec{\nabla}T_0 = \vec{0}$). It outlines then the effects of the magnetic field curvature on the results of Lemaire (1999) where the magnetic field lines were assumed to be straight lines as in the pioneering study of Newcomb (1961).

When $\vec{\nabla}T_0 = \vec{0}$, the stability criterion (5) for all quasi-interchange modes (transverse and translational interchange modes together) is given by

$$(\vec{g} - 2C_s^2\vec{c}_0) \cdot \left(\frac{\vec{\nabla}\rho_0}{\rho_0} - \frac{\vec{g}}{C_s^2}\right) \geqslant 0, \tag{7}$$

whereas the stability criterion of type 1 quasi-interchange mode (transverse interchange mode) alone is rewritten as

$$(\vec{g} - 2C_s^2\vec{c}_0) \cdot \left(\frac{\vec{\nabla}\rho_0}{\rho_0} - \frac{\vec{g} + 2V_A^2\vec{c}_0}{V_A^2 + C_s^2}\right) \geqslant 0. \tag{8}$$

We see that the key factor governing the stability is no more the direction of the effective gravity vector $\vec{g}$ as in Eqs. (1) and (2), but the direction of the vector $\vec{g} - 2C_s^2\vec{c}_0$ whose component transverse to the magnetic field lines is dominated by the magnetic curvature term in realistic configurations, unless the plasma is assumed to be cold ($C_s^2 = 0$) as in ideal magnetohydrodynamics convection models. As the reader can easily infer, this property will in particular have important consequence on Lemaire (1999, 2001) investigation and significantly alter their conclusions (cf. Section 5).

4.4. Stability criteria for a collisionless gyrotropic plasma

An important property of magnetospheric plasmas is the rarity of particle collisions, which tends to keep the thermal pressure anisotropic. Over long timescales on which convective instabilities operate, the rapid gyromotion of charged particles about magnetic field lines guarantees pressure isotropy in planes perpendicular to the magnetic field direction. Consequently, the plasma thermal pressure has two distinct components, respectively, perpendicular ($P_{\perp}$) and parallel ($P_{\parallel}$) to the magnetic field, and it is said to be gyrotropic. Perpendicular and parallel temperatures ($T_{\perp}$ and $T_{\parallel}$) can then also be defined as usual by $T_{\perp,\parallel} = P_{\perp,\parallel}/kn$.

The overall stability criterion for all quasi-interchange modes in collisionless gyrotropic proton–electron plasmas has been derived in Ferrière and André (2003) using the same assumptions as those described in Section 4.3. Ferrière and André (2003) have shown the existence of situations where two, one, or none of the three quasi-interchange modes (one transverse and two translational modes) can become unstable (cf. their Table 2). Anticipating the situation met in the application of

Section 5.2, only the first three lines of this table need to be considered in the current study. Accordingly, one and only one quasi-interchange mode (the transverse one or one translational one) can become unstable.

The overall stability criterion for all quasi-interchange modes consists here of the superposition of a criterion against instabilities triggered by thermal pressure anisotropies (corresponding to the firehose and mirror stability conditions in a uniform medium) and of an additional criterion due to stratification. The threefold condition for overall stability for all quasi-interchange mode is given by

$$F \geqslant 0, \tag{9a}$$

$$M \geqslant 0, \tag{9b}$$

$$\begin{aligned}
&[\vec{g} - (C_\perp^2 + C_\parallel^2)\vec{c}_0] \cdot \frac{\vec{\nabla}\rho_0}{\rho_0} \\
&\quad \geqslant \frac{[(1 - C_\perp^2/C_\parallel^2)\vec{g} + F\vec{c}_0]^2}{M} \\
&\quad + \left(C_\perp^2 \frac{\vec{\nabla}T_\perp}{T_\perp} + C_\parallel^2 \frac{\vec{\nabla}T_\parallel}{T_\parallel} \right) \cdot \vec{c}_0 \\
&\quad + \frac{\vec{g}^2}{C_\parallel^2} - 2\vec{g} \cdot \vec{c}_0 - F\vec{c}_0 \cdot \vec{c}_0,
\end{aligned} \tag{9c}$$

whereas the stability criterion for type 1 mode (transverse interchange mode) alone is given by

$$F \geqslant 0, \tag{10a}$$

$$\begin{aligned}
&[\vec{g} - (C_\perp^2 + C_\parallel^2)\vec{c}_0] \cdot \frac{\vec{\nabla}\rho_0}{\rho_0} \\
&\quad \geqslant \frac{[\vec{g} + (V_A^2 - C_\parallel^2)\vec{c}_0]^2}{V_A^2 + 2C_\perp^2} \\
&\quad + \left(C_\perp^2 \frac{\vec{\nabla}T_\perp}{T_\perp} + C_\parallel^2 \frac{\vec{\nabla}T_\parallel}{T_\parallel} \right) \cdot \vec{c}_0 \\
&\quad - (F + 3\, C_\parallel^2)\vec{c}_0 \cdot \vec{c}_0,
\end{aligned} \tag{10b}$$

where $F = (V_A^2 + C_\perp^2 - C_\parallel^2)$ and $M = (V_A^2 + 2C_\perp^2 - C_\perp^4/C_\parallel^2 - (\sum_s C_{s\perp}^4/C_{s\parallel}^2))$ are, respectively, the firehose and mirror parameters. These two parameters depend on the Alfvén speed squared, and on the perpendicular and parallel sound speeds squared of the whole plasma ($C_\perp^2 = P_{\perp 0}/\rho_0$ and $C_\parallel^2 = P_{\parallel 0}/\rho_0$). They depend also on the perpendicular and parallel sound speeds squared of the individual species denoted with a subscript s ($C_{s\perp}^2$ and $C_{s\parallel}^2$).

Note that the stability criteria obtained in the case of collisional plasmas can be recovered, provided that $P_\perp$ to $P_\parallel$, and the terms $2C_\perp^2$, $3C_\parallel^2$ are replaced by C_s^2. The stability criteria of quasi-interchange modes have also been obtained recently in the case of multicomponent gyrotropic plasmas (André and Ferrière, 2004), but since their expressions will not be used in the present study, they will not be repeated here.

The magnetostatic equilibrium condition reads in that case

$$\vec{g} + F\vec{c}_0 = \frac{\vec{\nabla}_\perp(P_{M0} + P_{\perp 0})}{\rho_0}. \tag{11}$$

In the following section, we apply these stability criteria to the various plasmaspheric distributions presented and discussed in Section 2. The aim of this exercise is to test the convective stability of the different plasmaspheric models versus quasi-interchange modes.

5. Convective instabilities in the plasmasphere

The stability criteria are functions of the local position in the plasmasphere, since they depend on the distributions of the effective gravity $\vec{g}$, the magnetic field $\vec{B}_0$, the density ρ_0 and of the thermal pressures $P_{\perp,\parallel 0}$ at equilibrium. We will check the stability criteria in the equatorial plasmasphere where $\vec{g}$ and $\vec{c}_0$ are coplanar. At other places in the plasmasphere some of the assumptions made are not valid and it may be premature to extend our conclusions to other locations outside the equatorial plane.

For the effective gravity in the equatorial plane, we take

$$g(L) = -\frac{GM_e}{R_e^2} L^{-2} + \Omega^2 R_e L, \tag{12}$$

with M_e the Earth's mass, R_e the Earth's equatorial radius, $L = R/R_e$, and Ω the rotation rate of the plasma.

The distance L_0 where the effective gravity changes sign is given by

$$L_0 = \left(\frac{GM_e}{\Omega^2 R_e^3} \right)^{1/3}, \tag{13}$$

and is equal to 6.6 in the case of a corotating plasma.

For the equilibrium magnetic field, we simply assume that the magnetic field is a centered dipole, such that the magnetic field strength and curvature at the equator are given by

$$B_0(L) = B_e L^{-3}, \tag{14}$$

$$c_0(L) = -\frac{3}{R_e} L^{-1}, \tag{15}$$

with B_e (31 000 nT) the equatorial magnetic field strength at the surface of the Earth.

The equilibrium density and thermal pressures correspond to the different plasmaspheric models described in Section 2.

5.1. Diffusive equilibrium model

We use the same hydrostatic/barometric equatorial density profile as that used by Lemaire (1999, 2001), where the particle distribution functions are assumed to be isotropic Lorentzians with a kappa index equal to 4, both for electrons and protons. For simplicity, the temperature (4000 K) and electron and ion density (3900 cm^{-3}) at a reference altitude of 2000 km ($L = 1.3$) are all assumed to be independent of the latitude. For order of magnitude calculations, this is a satisfactory first approximation. We assume also a corotating plasmasphere with $\Omega = \Omega_e$, the rotation rate of the Earth.

5.1.1. Gravity only

When applied to this model, the estimated stability criteria (Eqs. (1) and (2)) delineate different stability regions in the plane $[L, -\nabla\rho_0/\rho_0]$, represented in Fig. 3.

The thick solid black line corresponds to the equatorial density slope versus L in the diffusive equilibrium model. It can be seen that according to the stability criteria (1) and (2), the diffusive equilibrium appears to be convectively stable (locally) with respect to all quasi-interchange modes (and consequently to type 1 quasi-interchange mode) for all L. Beyond $L = L_0 = 6.6$, the diffusive model has a positive density gradient. Since all equatorial plasmaspheric density profiles (even during quiet magnetic conditions) have negative density slopes beyond $L = 6.6$, they cannot be in barometric equilibrium at large distances, indeed a corresponding increase of the plasma density with distance was never observed.

The slope of the observed electron density derived from Carpenter and Anderson empirical model is independent of L and equal to $d \ln n/dL = -0.724$; it maps as a horizontal line out of the frame of Fig. 3. This observed distribution is therefore stable with respect to types 1 and 2 quasi-interchange modes for $L<6.6$ and unstable with respect to type 1 quasi-interchange mode (transverse interchange mode) for $L>6.6$. The same conclusions will be obtained with any of the other models described in Section 2.3.

5.1.2. Combined effect of gravity and curvature

Let us now include the effects of the curvature of magnetic field lines. The stability criteria (7) and (8) delineate then different stability regions in the plane $[L, -\nabla\rho_0/\rho_0]$; they are represented in Fig. 4.

The diffusive equilibrium model illustrated by the thick solid black line appears now to be (locally) stable with respect to all quasi-interchange modes (including type 1 or transverse quasi-interchange mode) for $L>6.6$. It is, however, unstable with respect to type 2 or translational quasi-interchange mode for $L<6.6$. The empirical distribution of Carpenter and Anderson now appears (locally) unstable with respect to type 2 quasi-interchange mode for $L<8.3$ and also with respect to type 1 or transverse quasi-interchange mode for $L>8.3$. The comparison of Figs. 3 and 4 indicates that the

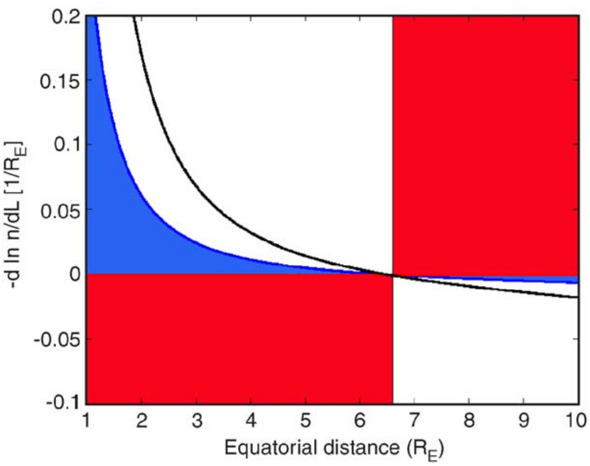

Fig. 3. Density slope thresholds for all quasi-interchange modes and for type 1 mode only in the plane $[L, -d \ln n/dL]$ for isotropic Lorentzian distributions with $\kappa_i = \kappa_e = 4$ and $\Omega = \Omega_e$, delimiting the domains where the stability criterion of all quasi-interchange modes is not fulfilled (in blue) and where only the stability criterion of type 1 quasi-interchange mode (transverse interchange mode) is not fulfilled (in red). Only the effects of the effective gravity are considered here; magnetic field lines are assumed to be straight: $c_0 = 0$.

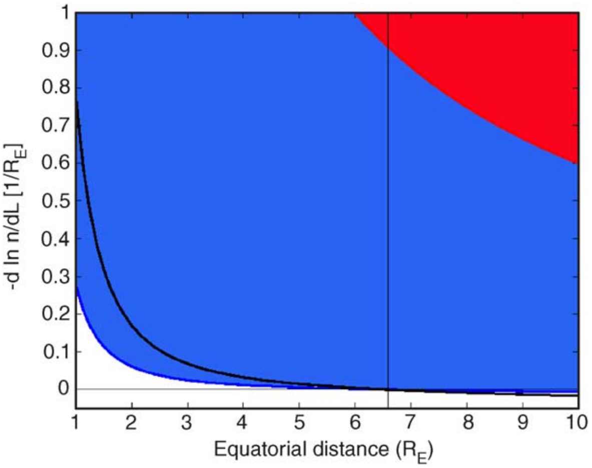

Fig. 4. Same as in Fig. 3, but with both the effects of the effective gravity and of the magnetic curvature considered.

curvature of the magnetic field lines plays a crucial role.

These results support the existence of a plasmaspheric wind till deep inside the magnetosphere as suggested by Lemaire and Schunk (1992). Our results also indicate that in that case it is not the transverse interchange mode that is unstable inside the plasmasphere but the translational mode corresponding predominantly to field-aligned ionization flows.

If we had considered any of the other empirical models described in Section 2.3, e.g. the one reported in Reinisch et al. (2004), the associated distribution will appear unstable with respect to type 2 quasi-interchange mode for smaller L, e.g. $L<4$, and also with respect to type 1 or transverse quasi-interchange mode for $L>4$. However, in that case, the plasmasphere is probably contracted and it is very likely that the plasmapause is located very close to the critical distance $L=4$. Consequently, except maybe in its outermost regions and close to the plasmapause, the plasmasphere is unstable not with respect to the transverse mode but to the translational mode.

5.1.3. Isothermal plasma distribution in magnetostatic equilibrium

It has been pointed out that in the case of an isothermal plasma, the sign of the vector $\vec{g}-2C_s^2\vec{c}_0$ is an important factor determining the stability of the quasi-interchange modes (Eqs. (7) and (8)). In order to check the relative importance of the magnetic curvature term compared to the effective gravity, we consider isothermal proton (subscript i) and electron (subscript e) distributions with $T=T_i=T_e=4000\,\mathrm{K}$ and $\gamma=\gamma_i=\gamma_e=\frac{5}{3}$.

The ratio between the curvature term and the purely gravitational one is written as

$$\frac{2C_s^2c_0}{GM_e/R_e^2L^2}=\left(12\,\frac{\gamma kT/m}{GM}\,R_e\right)L\simeq 12L, \tag{16}$$

whereas the ratio between the curvature term and the centrifugal one gives

$$\frac{2C_s^2c}{\Omega^2R_eL}=\left(12\,\frac{\gamma(kT/m)}{\Omega^2R_e^2}\right)\frac{1}{L^2}\simeq\frac{3000}{L^2}. \tag{17}$$

Since both these ratios are very large over the range of radial distance considered, we conclude that the effects of the magnetic curvature are largely dominant over the effects of the effective gravity, and that the vector $\vec{g}-2C_s^2\vec{c}_0$ is always directed outwardly.

Moreover, since $V_A^2\geqslant C_s^2$, the stability criterion (8) for type 1 quasi-interchange mode (transverse interchange mode) can be approximated by

$$(\vec{g}-2C_s^2\vec{c}_0)\cdot\left(\frac{\vec{\nabla}\rho_0}{\rho_0}-2\vec{c}_0\right)\geqslant 0. \tag{18}$$

This happens to be a good approximation of Eq. (8) because the plasma beta is small compared to unity. When the density gradient is given by the empirical model of Carpenter and Anderson, the equatorial distance where the second factor of the above stability criterion changes sign is equal to $8.3R_e$, which is also the equatorial distance found to play a critical role in our previous application. In the case of the larger density gradients given by the other models described in Section 2.3, the equatorial distance where the second factor of the above stability criterion changes sign is even smaller ($4R_e$).

5.2. Exospheric equilibrium model

The hydrostatic η-exospheric model of Pierrard and Lemaire (2001) aims at reproducing exactly the empirical density distribution of Carpenter and Anderson. It gives gyrotropic pressure distributions that are not accessible via observations. Both the firehose F and mirror M parameters (that are included in Eqs. (9) and (10) of the stability criteria for quasi-interchange modes) have positive values for this model.

The stability criteria applied to this model delineate different stability regions in the plane $[L,-\nabla\rho_0/\rho_0]$; they are illustrated in Fig. 5. The

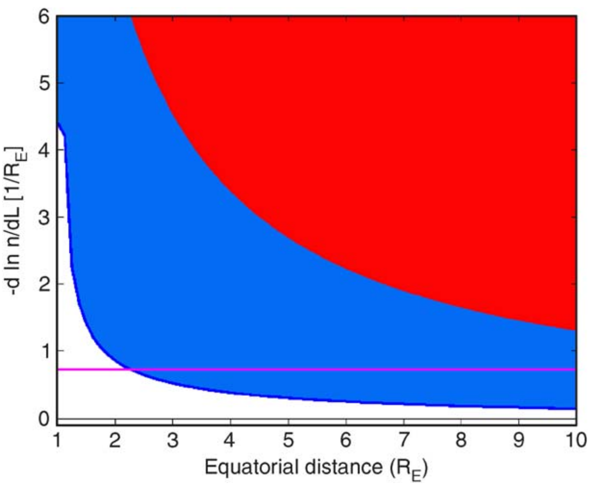

Fig. 5. Same as in Fig. 4, but for the exospheric model of Pierrard and Pierrard and Lemaire (2001).

magenta horizontal line corresponds to Carpenter and Anderson constant density slope as well as that of the η-exospheric model.

The η-exospheric model appears (locally) unstable with respect to type 2 or translational quasi-interchange mode for $L > 2.3$, whereas it appears stable with respect to type 1 or transverse quasi-interchange mode for all L. If the effects of the magnetic curvature are not included (results not shown), our results would be altered in the following manner: the η-exospheric model would appear stable against all types of quasi-interchange modes for $L < 6.6$, and unstable with respect to type 1 quasi-interchange mode for $L > 6.6$. These results lead us again to the conclusion that hydrostatic equilibrium is convectively unstable and therefore support the existence of a plasmaspheric wind deep inside the plasmasphere.

6. Conclusions

Different equatorial density profiles have been used and discussed in the present work in order to pursue Lemaire and Schunk (1992, 1994) and Lemaire (1999, 2001) analysis. The effects of non-electromagnetic forces, of curvature of the magnetic field lines, and of stratification of the plasma distribution in driving convective instabilities, have been presented first from a theoretical point of view. A broader class of modes can be destabilized at nearly perpendicular wavevector; they can give rise to interchange motions triggered more easily than the pure interchange mode initially introduced by Gold (1959). These modes for which $k_{\parallel} \neq 0$ are known as quasi-interchange modes; they belong to two types depending on their behavior in the limit of zero parallel wave vector, $k_{\parallel} \to 0$. Type 1 quasi-interchange mode or transverse interchange mode corresponds to plasma motions which are predominantly perpendicular to magnetic field lines and results in the exchange of plasma elements across magnetic field lines. Type 2 quasi-interchange mode or translational mode corresponds to motions of the plasma predominantly along flux tubes. The (local) stability criteria of these quasi-interchange modes have been made explicit, as well as the restrictive assumptions behind their derivation: static equilibrium, invariance of the equilibrium parameters along field lines, gravity parallel to curvature.

These assumptions are satisfied in the equatorial plane of the plasmasphere but not at higher altitudes along magnetic field lines. Thus, it would be premature to extend to the whole plasmasphere the stability criteria that we derived here for the equatorial region and where these assumptions are likely to be satisfied.

We have tested the (local) stability with respect to quasi-interchange modes for diffusive and exospheric hydrostatic field-aligned density distributions expected to be representative of the equatorial regions of the plasmasphere under very quiet magnetic conditions. When the curvature of magnetic field lines is properly taken into account, the conclusions obtained by Lemaire (1999, 2001) for straight field lines are significantly altered since the magnetic curvature is found to have a much larger influence than the effective gravity in the Earth magnetosphere.

Type 2 quasi-interchange mode or translational mode appears to play a more important role than type 1 quasi-interchange mode or transverse mode. Type 2 mode appears unstable both in the case of Lemaire (1999, 2001) diffusive model for $L < 6.6$ and in the case of Pierrard and Lemaire (2001) η-exospheric model for $L > 2.3$. Since the last model fits the empirical distribution of Carpenter and Anderson (1992), the later conclusion holds also in that case. Similar conclusions are obtained with other empirical models characterized by larger density gradients (e.g. Reinisch et al., 2004). Consequently, the picture of a static plasmasphere seems to be at odd, even in a saturated stage following a long period of quiet magnetic conditions.

Although type 2 quasi-interchange mode or translational mode is considered primarily to lead to plasma motions parallel to the magnetic field line, it has been pointed out by Ferrière et al. (1999) that it does not imply strictly parallel motions but that the motion necessarily acquires also a transverse component. In that sense, this would be compatible with the concept of plasmaspheric wind introduced by Lemaire and Schunk (1992), consisting of a slow and permanent cross-L transport of plasma from the inner to the outer equatorial regions of the plasmasphere accompanied by a field-aligned upward ionization flow.

As indicated above, our application suffers from large uncertainties due to the use of various simplifying assumptions and to the neglect of several effects. Clearly, there is more work ahead of us, and additional assumptions to relax, but interesting conclusions can already be drawn from this simplified formulation. Furthermore, we have so far only considered the presence of the low-energy plasma of ionospheric energy, without taking explicitly into account the presence of hot plasma inside the regions considered. The coupling of the low-energy plasma with the higher-energy plasma is known to give rise to wave–particle interactions. The subtle impact of hot plasma pressure and its gradient on the stability criteria of quasi-interchange modes has not yet been investigated, through for example the use of a self-consistent model for plasma and field distributions.

Finally, all the stability criteria considered in our study happen to be local; they do not include the ionospheric effects arising at the foot of the flux tubes that could eventually play a stabilizing role. A global approach is certainly required to access the overall dynamics of the plasmasphere. This region is currently being revisited by the Image and Cluster missions. These missions are giving in particular further and more detailed insights on this dynamics.

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References

André, N., 2003. Ondes et instabilités basse-fréquence dans un plasma gyrotrope. Application à l'instabilité d'interchange dans les magnétosphères des planètes géantes. Ph.D. Thesis, Université Paul Sabatier.

André, N., Ferrière, K.M., 2004. Low-frequency waves and instabilities in stratified, gyrotropic, multicomponent plasmas: theory and application to the plasma transport in the Io torus. Journal of Geophysical Research 109, A12225.

Angerami, J.J., Carpenter, D.L., 1966. Whistler studies of the plasmapause in the magnetosphere, 2, Equatorial density and total tube electron content near the knee in magnetospheric ionization. Journal of Geophysical Research 71, 711.

Carpenter, D.L., Anderson, R.R., 1992. An ISEE/Whistler model of equatorial electron density in the magnetosphere. Journal of Geophysical Research 97, 1097–1108.

Carpenter, D.L., Anderson, R.R., Bell, T.F., Miller, T.R., 1981. A comparison of equatorial densities measured by whistlers and by a satellite radio technique. Geophysical Research Letters 8, 1107.

Chappell, C.R., Harris, K.K., Sharp, G.W., 1970. A study of the influence of magnetic activity on the location of the plasmapause as measured by OGO 5. Journal of Geophysical Research 75, 50.

Cheng, A.F., 1985. Magnetospheric interchange instability. Journal of Geophysical Research 90, 9900.

Corcuff, P., Corcuff, Y., Carpenter, D.L., Chappell, C.R., Vigneron, J., Kleimenova, N., 1972. La plasmasphère en période de recouvrement magnétique. Etude combinée des données des satellites OGO 4, OGO 5 et des sifflements reçus au sol. Annales de Geophysique 28, 679–696.

Ferrière, K.M., André, N., 2003. A mixed magnetohydrodynamic-kinetic theory of low-frequency waves and instabilities in stratified, gyrotropic, two-component plasmas. Journal of Geophysical Research 108, 1308.

Ferrière, K.M., Zimmer, C., Blanc, M., 1999. Magnetohydrodynamic waves and gravitational/centrifugal instability in rotating magnetospheres. Journal of Geophysical Research 104 (17), 335.

Gallagher, D.L., Craven, P.D., Comfort, R.H., 2000. Global core model. Journal of Geophysical Research 105 (18), 819.

Gold, T., 1959. Motions in the magnetosphere of the Earth. Journal of Geophysical Research 64, 1219.

Huang, X., Reinisch, B.W., Song, P., Green, J.L., Gallagher, D.L., 2004. Developing an empirical density model of the plasmasphere using IMAGE/RPI observations. Advances in Space Research 33, 829.

Lemaire, J.F., 1976. Rotating ion-exosphere. Planetary and Space Science 24, 97.

Lemaire, J.F., 1989. Plasma distribution models in a rotating magnetic dipole and refilling of plasmaspheric flux tubes. Physics of Fluids B 1, 1519.

Lemaire, J.F., 1999. Hydrostatic equilibrium and convective stability in the plasmasphere. Journal of Atmospheric and Solar-Terrestrial Physics 61, 867–878.

Lemaire, J.F., 2001. Corrigendum to "Hydrostatic equilibrium and convective stability in the plasmasphere" [Journal of Atmospheric and Solar-Terrestrial Physics 61 (1999) 867–878]. Journal of Atmospheric and Solar-Terrestrial Physics 63, 2007.

Lemaire, J.F., Scherer, M., 1974. Exospheric models of the topside ionosphere. Space Science Reviews 15, 591.

Lemaire, J.F., Schunk, R.W., 1992. Plasmaspheric wind. Journal of Atmospheric and Solar-Terrestrial Physics 54, 467–477.

Lemaire, J.F., Schunk, R.W., 1994. Plasmaspheric convection with non-closed field lines. Journal of Atmospheric and Solar-Terrestrial Physics 56, 1629–1633.

Liu, W.W., 1997. Physics of the explosive growth phase: ballooning instability revisited. Journal of Geophysical Research 102, 4927.

McIlwain, C.E., 1986. A Kp dependent equatorial electric field model. Advances in Space Research 6, 187.

Newcomb, W.A., 1961. Convective instability induced by gravity in a plasma with frozen-in field lines. Physics of Fluids 4, 391.

Pannekoek, A., 1922. Ionization in stellar atmospheres. Bulletin Astronomical Institute Mathematics 1, 107.

Park, C.G., 1970. Whistler observations of the interchange of ionization between the ionosphere and the protonosphere. Journal of Geophysical Research 75, 4249.

Park, C.G., 1973. Whistler observations of the depletion of the plasmasphere during a magnetospheric substorm. Journal of Geophysical Research 78, 672.

Park, C.G., 1974a. Some features of plasma distribution in the plasmasphere deduced from Antarctic whistlers. Journal of Geophysical Research 79, 169.

Park, C.G., 1974b. A morphological study of substorm-associated disturbances in the ionosphere. Journal of Geophysical Research 79, 2821.

Pierrard, V., Lemaire, J.F., 1996. Lorentzian ion-exosphere models. Journal of Geophysical Research 101, 7923–7934.

Pierrard, V., Lemaire, J.F., 2001. Exospheric model of the plasmasphere. Journal of Atmospheric Solar-Terrestrial Physics 63, 1261.

Reinisch, B.W., Huang, X., Song, P., Green, J.L., Fung, S.F., Vasyliunas, V.M., Gallagher, D.L., Sandel, B.R., 2004. Plasmaspheric mass loss and refilling as a result of a magnetic storm. Journal of Geophysical Research 109, A01202.

Rosseland, S., 1924. Electrical state of a star. Monthly Notices Royal Astronomical Society 84, 70.

Smilauer, J., Truhlik, V., Triskova, L., 2002. Thermal plasma measurements onboard the MAGION-5 satellite: a possible plasmasphere data source. Advances in Space Research 29, 887.

Sojka, J.J., Wrenn, G.L., 1985. Refilling of geosynchronous flux tubes as observed at the equator by GEOS 2. Journal of Geophysical Research 90, 6379–6385.

Southwood, D.J., Kivelson, M.G., 1987. Magnetospheric interchange instability. Journal of Geophysical Research 92, 109.

Tarcsai, G., 1985. Ionosphere-plasmasphere electron fluxes at middle latitudes obtained from whistlers. Advances in Space Research 5, 155–158.

Titheridge, J.E., 1976. Plasmapause effects in the topside ionosphere. Journal of Geophysical Research 81, 3227.