Ballooning-Mirror Instability and Internally Driven Pc 4-5 Wave Events

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Abstract

A kinetic-MHD field-aligned eigenmode stability analysis of low frequency ballooning-mirror instabilities has been performed for anisotropic pressure plasmas in the magnetosphere. The ballooning mode is mainly a transverse wave driven unstable by pressure gradient in the bad curvature region. The mirror mode with a dominant compressional magnetic field perturbation is excited when the product of plasma beta and pressure anisotropy ($P_{\perp}/P_{\parallel} > 1$) is large. In the limit that the wave frequency is smaller than the energetic trapped particle magnetic drift frequency, which is usually much smaller than the energetic trapped particle bounce frequency, the energetic trapped particles experience the bounce-averaged wave structure due to their rapid bounce motion. For modes with north-south symmetric field-aligned structure of parallel perturbed magnetic field the energetic trapped particle kinetic pressure response is finite and cancels with their fluid pressure response so that the symmetric mode is stable. Physically the energetic trapped particles precess very rapidly across the $\vec{B}$ field, and their motion becomes very rigid with respect to low frequency symmetric MHD perturbations. For antisymmetric modes the energetic trapped particle kinetic pressure response from the northern hemisphere cancels with that from the southern hemisphere in a bounce period, and the instability β threshold of the antisymmetric mode is determined by the energetic particle fluid free energy. Pressure anisotropy with $P_{\perp}/P_{\parallel} > 1$ reduces the $\beta_{\parallel}$ threshold. The antisymmetric mode changes from a ballooning mode with dominant transverse magnetic field components at $P_{\perp}/P_{\parallel} = 1$ to a hybrid ballooning-mirror type mode with comparable transverse and compressional magnetic field components near the equator as $P_{\perp}/P_{\parallel}$ increases. With large equatorial plasma beta ($\beta_{\parallel} \geq O(1)$) and pressure anisotropy ($P_{\perp}/P_{\parallel} > 1$) the field-aligned wave structure of antisymmetric ballooning-mirror mode resembles the multisatellite observations of a long lasting compressional Pc 5 wave event during November 14-15, 1979 [Takahashi et al., 1987]. From the AMPTE/CCE particle and magnetic field data observed during Pc 4-5 wave events we compute the ballooning-mirror instability parameters and perform a correlation study with the theoretical instability threshold. We find that compressional Pc 5 waves approximately satisfy the ballooning-mirror instability condition, and transverse Pc 4-5 waves are probably related to resonant ballooning instabilities with small pressure anisotropy.

1. Introduction

Internally driven Pc 4-5 waves usually have large azimuthal mode numbers on the order of 100 and are mainly observed in the magnetosphere by satellites [Takahashi, 1988]. There are two types of internally driven ULF waves; one has a dominant compressional magnetic field component, and the other has a dominant transverse component. Compressional Pc 5 magnetic perturbations [Walker et al., 1982; Allan et al., 1982; Nagano and Araki, 1983; Misra et al., 1985; Lin and Barfield, 1985; Takahashi et al., 1985a, 1985b, 1987; Higuchi et al., 1986] with periods in the range of 150-600 seconds were believed to be driven by mirror-type instabilities [Hasegawa, 1969; Cheng and Lin, 1987]. The highly compressional magnetic perturbations are usually observed around the earth's magnetic equator near geosynchronous orbit during periods of enhanced ring current intensity and are associated with high beta, anisotropic pressure plasmas with $P_{\perp} > P_{\parallel}$, where the subscripts $\perp$ and $\parallel$ denote the components perpendicular and parallel to the ambient magnetic field respectively. Significant progress has been made in the multisatellite observation of a long lasting compressional Pc 5 wave event during November 14-15, 1979 [Takahashi et al., 1987; Takahashi, 1988; Takahashi et al., 1990b] which revealed the field-aligned structures of the compressional magnetic field $\delta B_{\parallel}$ to be antisymmetric with respect to the earth's magnetic equator with a full latitudinal range of about 20° . The smaller transverse magnetic components, radial component δB_{ψ} and azimuthal component δB_{ϕ} , have a symmetric parity and their polarization varies with the magnetic latitude. The wave frequencies are about one order of magnitude smaller than the shear Alfvén frequency obtained from the measured plasma density and wave structures along the ambient magnetic field at geosynchronous orbit.

The internally driven Pc 4-5 transverse waves usually have low frequency and dominant radial polarization, and they are believed to have similar (but more extended) field-aligned wave symmetry properties as the compressional Pc 5 waves [Engebretson et al., 1988; Takahashi et al., 1990a].

Linear theories of internally driven compressional Alfvén type instabilities have been presented in terms of (1) mirror instabilities due to pressure anisotropy [Hasegawa, 1969; Pokhotelov et al., 1986; Cheng and Lin, 1987], (2) drift compressional instabilities due to pressure nonuniformity [Hasegawa, 1971; Ng et al., 1984; Cheng and Lin, 1987], (3) trapped particle bounce and magnetic drift resonance excitation of ULF waves [Southwood, 1976; Chen and Hasegawa, 1991], and (4) the ballooning-mirror instability [Cheng and Qian, 1993]. A potential candidate for explaining internally driven transverse Alfvén type instabilities is the ballooning mode [Miura et al., 1989; Lee and Wolf, 1992; Cheng and Qian, 1993]. In general the transverse and

compressional magnetic fields couple, and the ballooning and mirror modes are limiting cases of the general ballooning-mirror instability [Cheng and Qian, 1993].

Two coupled kinetic-MHD eigenmode equations have been derived [Cheng and Lin, 1987; Cheng, 1991, Chen and Hasegawa, 1991] to describe the coupling between the transverse and the compressional magnetic field components. The transverse magnetic field equation shows that the shear Alfvén type wave can be destabilized by the combined effect of the magnetic field curvature and the plasma pressure gradient to excite the ballooning mode. The compressional magnetic field equation indicates that the mirror mode can be destabilized by the combined effect of plasma beta and pressure anisotropy ($P_{\perp} > P_{\parallel}$). The coupling between the compressional and transverse magnetic field components is due to finite perpendicular pressure gradient and the kinetic trapped particle perturbed pressures. The kinetic effects associated with the energetic trapped particles play an essential role in determining the stability and structure of the ballooning-mirror mode.

Cheng and Qian [1993] have performed analytical and numerical eigenmode analyses of ballooning-mirror mode that take into account the coupling between the transverse ballooning and the compressional mirror modes in anisotropic pressure plasmas along the ambient magnetic field. The ballooning-mirror mode frequency is assumed to be smaller than the energetic particle magnetic drift frequency, which is usually much smaller than the energetic trapped particle bounce frequency. Without the kinetic effects we show that the MHD mode with symmetric structure of parallel perturbed magnetic field $\delta B_{\parallel}$ and electrostatic potential Φ along the north-south ambient magnetic field is more unstable than the antisymmetric mode. However, if energetic trapped particle kinetic effects are included, the symmetric ballooning-mirror mode is completely stabilized. On the other hand, the antisymmetric ballooning-mirror mode is only weakly influenced by energetic trapped particle kinetic effects and remains unstable. For symmetric modes, the energetic trapped particles experience the bounce-averaged wave structure due to their rapid bounce motion, and their nonadiabatic kinetic pressure response cancels with their perturbed fluid pressure response so that they don't contribute to drive the instability of the symmetric mode. Physically the energetic trapped particle stabilization of the symmetric mode results from the condition that the energetic trapped particles drift very rapidly across the $\vec{B}$ field, and their motion becomes very rigid with respect to low frequency symmetric MHD perturbations. For antisymmetric modes, the energetic trapped particle nonadiabatic kinetic pressure response from the northern hemisphere cancels with that from the southern hemisphere in a bounce period, and thus the instability β threshold is mainly determined by the energetic particle fluid free energy.

The field-aligned perturbed magnetic field structure of the antisymmetric mode changes from a ballooning mode with dominant transverse magnetic field component at $T_{\perp}/T_{\parallel} = 1$ to a mixed mirror-ballooning type mode with comparable transverse and compressional magnetic field components near the equator as $T_{\perp}/T_{\parallel}$ increases. As $T_{\perp}/T_{\parallel}$ increases, the amplitudes of the parallel magnetic field component $\delta B_{\parallel}$ and the azimuthal component δB_{ϕ} increase, and the mode also becomes more localized near the equator. At large values of $T_{\perp}/T_{\parallel}$ the theoretical eigenmode structure resembles the field-aligned wave structure (all three perturbed magnetic field components) of the multisatellite (SCATHA, GOES2, GOES3, GEOS2) observations of a long lasting compressional Pc 5 wave event during November 14-15, 1979 [Takahashi et al., 1987; Takahashi, et al., 1990b] in the ring current region.

Chen and Hasegawa [1991] proposed that the perturbed compressional magnetic field with antisymmetric field-aligned structure can be excited by the drift Alfvén ballooning mirror instability that is destabilized by hot particle pressure gradient via the magnetic drift-bounce resonance. The drift Alfvén ballooning mirror instability may have lower pressure anisotropy threshold than the ballooning-mirror instability. The relationship between the ballooning-mirror mode and the drift Alfvén ballooning-mirror mode has still not yet been resolved. Even though no realistic drift Alfvén ballooning-mirror mode stability calculation has been performed, it is conjectured that the drift Alfvén ballooning mirror instability may have a slightly lower pressure anisotropy threshold than the ballooning-mirror instability. However, it is important that wave resonance with all particle species be included in the calculation before a definite answer on the stability threshold can be concluded.

Although significant progress has been made in the satellite observational data of Pc 4-5 waves and theoretical understandings of ULF waves, a close comparison of the plasma properties during wave activities between theory and observation has still not yet been performed. In the paper we present a correlation study between the theoretical ballooning-mirror instability threshold parameters and those obtained from satellite particle data during Pc 4-5 wave events. By comparing the observed plasma properties with the theoretical ballooning-mirror instability threshold one should be able to identify whether the internal excitation mechanism of observed Pc 4-5 waves is due to the ballooning-mirror instabilities.

From the AMPTE/CCE particle data and magnetic field observed during Pc 4-5 wave events we compute the instability parameters and perform a correlation study with the theoretical ballooning-mirror instability threshold parameters. It is nontrivial to compute the ballooning-mirror instability parameters from the measured particle distribution along a satellite's orbit. We

need to know how the ion distribution and the computed instability parameters associated with the ballooning-mirror instabilities change from the time interval of no wave activity to those of clear wave activity. By performing theoretical calculations based on the observed ion distributions we might be able to determine whether the wave is driven by pressure anisotropy, or pressure gradient. The results of the correlation studies indicate that the ballooning-mirror instabilities are responsible for the Pc 4-5 waves. The transverse wave is related to the resonant type ballooning mode at lower beta. The compressional wave is related to the hybrid ballooning-mirror mode excited when pressure gradient and pressure anisotropy ($P_{\perp}/P_{\parallel}$) are large.

The paper is organized as follows. In Sec. 2 we briefly review the results of a kinetic-MHD stability analysis of the ballooning-mirror mode [Cheng and Qian, 1993] that explains the observed wave structures in terms of predicted plasma parameters. Section 3 presents the results of the correlation study of particle data for both the transverse and the compressional wave events observed by AMPTE/CCE are presented. A summary and discussion is given in Sec. 4.

2. Ballooning-Mirror Instabilities

We consider a magnetospheric ring current plasma consisting of a core background component (electron and cold ions) and a hot ion component (hot proton and Oxygen) with the hot plasma density smaller than the core plasma density, $n_h \ll n_c$, and the hot plasma temperature larger than the core plasma temperature, $T_h \gg T_c$. For the ring current plasma near the geosynchronous orbit, typically the core plasma temperature is $T_c \approx 10 - 10^2$ eV, the hot plasma temperature is $T_h \approx 10^4 - 10^5$ eV, the ratio of the hot plasma density to the core plasma density is $(n_h/n_c) \approx 10^{-1}$, thus the ratio of core plasma beta to the hot plasma beta is $(\beta_c/\beta_h) \approx 10^{-2}$. Therefore, the plasma beta is dominated by the hot ion component. For such plasma its dynamic is most conveniently described by a kinetic-MHD model [Cheng, 1991].

If the plasma convection in the magnetosphere is small, the magnetospheric equilibrium can be approximated by a static MHD equilibrium with anisotropic pressure, which is described by the system of equations

$$\vec{J} \times \vec{B} = \nabla \cdot \vec{P} = \nabla P_{\perp} - \nabla \cdot [(P_{\perp} - P_{\parallel}) \hat{b} \hat{b}], \quad (1)$$

$$\nabla \times \vec{B} = \vec{J}, \quad (2)$$

$$\nabla \cdot \vec{B} = 0, \quad (3)$$

where $\hat{b}$ is a unit vector along an equilibrium magnetic field line, and $\vec{J}$, $\vec{B}$, and $\vec{P}$ are the equilibrium current, magnetic field, and pressure tensor, respectively.

For an axisymmetric magnetospheric equilibrium, the magnetic field can be expressed as $\vec{B} = \nabla\psi \times \nabla\phi$ and the equilibrium solution has been studied numerically by Cheng [1992]. For a dipole field the magnetic flux function given by $\psi = -M \sin^2\theta / r$, where r and θ are the radius and polar angle in the spherical coordinate system (r, θ, ϕ) , and M is the dipole moment. The components of the dipole magnetic field are given by $B_r = -2M \cos\theta / r^3$, and $B_\theta = -M \sin\theta / r^3$. For a collisionless plasma the particle energy ($\mathcal{E} = v^2/2$) and the adiabatic invariants, magnetic moment ($\mu = v_\perp^2 / 2B$) and the longitudinal invariant ($J_\parallel = \oint ds v_\parallel$), are constant during the drift motions, where $v_\parallel$ and $v_\perp$ are the components of the velocity parallel and perpendicular to $\vec{B}$, respectively. The guiding center equilibrium particle distribution function must have the form $F = F(\mathcal{E}, \mu, J_\parallel)$. In general, $J_\parallel = J_\parallel(\mathcal{E}, \mu, \psi, \alpha)$ and $F = F(\mathcal{E}, \mu, \psi, \alpha)$. If all particles on each field line share the same drift surface, where ψ labels the drift surface, then $J_\parallel = J_\parallel(\mathcal{E}, \mu, \psi)$ and $F = F(\mathcal{E}, \mu, \psi)$. The guiding-center particle distributions $F(\mathcal{E}, \mu, \psi)$ can be either prescribed by an analytical form or obtained from the satellite measurements of the particle flux. The equilibrium parallel and perpendicular pressures are defined by

$$\begin{pmatrix} P_\parallel \\ P_\perp \end{pmatrix} = \sum_{j, \sigma_\parallel} 2\pi m_j \int_0^\infty d\mathcal{E} \int_0^{\mathcal{E}/B} d\mu \left[B F_j / |v_\parallel| \right] \begin{pmatrix} 2(\mathcal{E} - \mu B) \\ \mu B \end{pmatrix}, \quad (4)$$

where the summation is over the particle species j and $\sigma_\parallel$ which represents the direction of particle velocity parallel to $\vec{B}$, and m_j is the particle mass. The parallel velocity $v_\parallel$ has the form

$$v_\parallel = \sigma_\parallel \sqrt{2(\mathcal{E} - \mu B)}. \quad (5)$$

By inspection $P_\perp$ and $P_\parallel$ are functions of ψ and B only. It is convenient to introduce the functions

$$\sigma \equiv 1 + (P_\perp - P_\parallel) / B^2, \quad (6)$$

and

$$\tau \equiv 1 + (1/B)(\partial P_\perp / \partial B)_\psi. \quad (7)$$

The momentum balance equation parallel to the equilibrium magnetic field is given by

$$\vec{B} \cdot \nabla P_{\parallel} = (P_{\parallel} - P_{\perp}) \hat{b} \cdot \nabla B. \quad (8)$$

Making use of Eqs. (6)-(8), the momentum balance equation perpendicular to the magnetic field is given by

$$\tau \nabla_{\perp} (B^2 / 2) + \tilde{\nabla}_{\perp} P_{\perp} = \vec{\kappa} \cdot \sigma B^2, \quad (9)$$

where $\tilde{\nabla} = \nabla - \nabla B (\partial/\partial B)_{\psi}$, $\vec{\kappa} = \hat{b} \cdot \nabla \hat{b}$ is the magnetic field curvature. Note that the parallel momentum balance equation, Eq. (8), is automatically satisfied if the particle distribution $F(\epsilon, \mu, \psi)$ is used to compute $P_{\perp}$ and $P_{\parallel}$. From Eq. (8), σ can be expressed as $\sigma = 1 - (1/B)(\partial P_{\parallel}/\partial B)_{\psi}$.

The linearized kinetic-MHD eigenmode equations for the low-frequency transverse and compressional Alfvén waves had been derived [Cheng and Lin, 1987; Cheng, 1991]. By assuming that the perpendicular wavelength is shorter than the parallel wavelength which is in turn shorter than the equilibrium scale length and the particle gyroradius is small compared to the perpendicular wavelength for all particle species, the perturbed guiding center particle distribution δf is determined from the drift kinetic equation. In the limit of zero parallel electric field the perturbed transverse magnetic field is related to the electrostatic potential Φ by $\delta \vec{B}_{\perp} \approx \nabla \times [\vec{B}(\vec{B} \cdot \nabla \Phi / \omega B^2)]$, where ω is the eigenmode frequency of the perturbed quantities which have a temporal dependence of $\exp(-i\omega t)$. We consider a WKB wave form perpendicular to the ambient magnetic field so that $\nabla_{\perp}$ operates only on the perturbed quantities and $\nabla_{\perp} = i \vec{k}_{\perp}$. The eigenmode equations for $\hat{\Phi}$ ($= \Phi/\omega$) and $\delta B_{\parallel}$ can be obtained from Eqs. (40), (41), and (45) in the paper by Cheng [1991] and are given by

$$\begin{aligned} \vec{B} \cdot \nabla \left(\frac{\sigma k_{\perp}^2}{B^2} \vec{B} \cdot \nabla \hat{\Phi} \right) + \frac{\rho k_{\perp}^2 \omega^2}{B^2} \hat{\Phi} \\ + \frac{(\vec{B} \times \vec{\kappa}) \cdot \vec{k}_{\perp}}{B^2} \left[\frac{\vec{B} \times \tilde{\nabla} P_{\parallel}}{B^2} \cdot \vec{k}_{\perp} \hat{\Phi} + \sigma B \delta B_{\parallel} - \delta p_{\parallel} \right] = 0, \end{aligned} \quad (10)$$

and

$$\begin{aligned} \vec{B} \cdot \nabla \left[\frac{\sigma}{B^2} \vec{B} \cdot \nabla \delta B_{\parallel} \right] + \frac{\rho \omega^2}{B^2} \delta B_{\parallel} \\ - k_{\perp}^2 \left[\tau \delta B_{\parallel} - \vec{k}_{\perp} \cdot \frac{\vec{B} \times \tilde{\nabla} P_{\perp}}{B^3} \hat{\Phi} + \frac{\delta \hat{p}_{\perp}}{B} \right] = 0, \end{aligned} \quad (11)$$

where ρ is the mass density, $\tilde{\nabla} = \nabla - \nabla B (\partial/\partial B)_{\psi}$. The kinetic effect due to trapped particles is included in the nonadiabatic perturbed pressures $\delta \hat{p}_{\perp}$ and $\delta \hat{p}_{\parallel}$ which are given by

$$\begin{pmatrix} \delta \hat{p}_{\parallel} \\ \delta \hat{p}_{\perp} \end{pmatrix} = \sum_j M \int d^3v \, \hat{g} \begin{pmatrix} 2(\varepsilon - \mu B) \\ \mu B \end{pmatrix}, \quad (12)$$

and in the absence of parallel electric field the drift kinetic equation for the linearized nonadiabatic particle distribution function $\hat{g}$ is given by

$$\left[\frac{\partial}{\partial t} + (\vec{v}_{\parallel} + \vec{v}_d) \cdot \nabla \right] \hat{g} = \left[\frac{e}{M} \frac{\partial F}{\partial \varepsilon} \frac{\partial}{\partial t} - \frac{\vec{B} \times \nabla F}{B^2} \cdot \nabla \right] Y, \quad (13)$$

where $Y = i \vec{v}_d \cdot \nabla \Phi / \omega - M \mu \delta B_{\parallel} / e$, $\vec{v}_d = (M \vec{B} / e B^2) \times [\nabla(\mu B) + \vec{\kappa} v_{\parallel}^2]$ is the particle magnetic drift velocity in the equilibrium magnetic field, and $\vec{\kappa} = (\vec{B}/B) \cdot \nabla (\vec{B}/B)$ is the equilibrium magnetic field curvature. In terms of a Fourier series representation the linearized nonadiabatic particle distribution function $\hat{g}$ has been derived for a magnetospheric geometry in the paper by Cheng [1991] (see Sec. 4 and Appendix C) and will not be repeated here..

Equations (10) and (11) describe the coupling between the compressional and transverse perturbed magnetic field due to finite magnetic field curvature, perpendicular pressure gradient, and the nonadiabatic trapped particle kinetic pressure responses $\delta \hat{p}_{\perp}$ and $\delta \hat{p}_{\parallel}$. Eq. (10) describes the transverse shear Alfvén type wave that can be destabilized by pressure gradient in a bad magnetic field curvature with $(\vec{\kappa} \cdot \nabla \psi) (\nabla P \cdot \nabla \psi) > 0$ to excite ballooning modes in a high β ($= O(1)$) nonuniform plasma. In Eq. (10) the first term represents the stabilizing field line bending effect for $\sigma > 0$, the second term represents the core plasma inertia, the third term represents the destabilization effect of pressure gradient in a bad magnetic field curvature, the $\delta B_{\parallel}$ term represents the coupling to the compressional Alfvén type wave, and the $\delta \hat{p}_{\parallel}$ term represents the nonadiabatic (kinetic) hot trapped particle parallel perturbed pressure. Equation (11) indicates that the

compressional Alfvén type waves can be destabilized by the the combined effect of plasma beta and pressure anisotropy to excite mirror modes. The mirror instability free energy is represented by the parameter τ defined in Eq.(7). In Eq. (11) the first term represents a stabilizing field line propagating effect for $\sigma > 0$, the second term represents the core plasma inertia, the third term represents the pressure anisotropy effect on the perpendicular propagation of compressional wave, the $\hat{\Phi}$ term represents the coupling to the shear Alfvén type wave, and the $\hat{\delta p}_\perp$ term represents the nonadiabatic (kinetic) hot trapped particle perpendicular perturbed pressure. If $\tau < 0$ mirror mode can be unstable with perturbation localized around the region where $\tau < 0$. Eqs. (10) and (11) are similar to the previously presented eigenmode equations [Berk et al., 1983; Cheng and Lin, 1987; Chen and Hasegawa, 1991]. However, we note that the first two terms of Eq.(11) were neglected in Eq. (21) of Chen and Hasegawa [1991]; the first term was neglected because they assumed that $k_\parallel^2 \ll \tau k_\perp^2$, and the second term was neglected because they employed the low frequency gyrokinetic equations that ignore compressional Alfvén type waves. In our studies, we retained these two terms in Eq.(11) to study the coupling between the ballooning and mirror modes even in the limit that τ goes to zero.

The stability of the antisymmetric ballooning-mirror mode is usually expressed in terms of parallel plasma beta $\beta_\parallel$ and temperature ratio $T_\perp/T_\parallel$ at equator. The stability property can also be expressed in terms of α_p and τ , where the new dimensionless parameter α_p is defined to describe the ballooning instability free energy and is given by

$$\alpha_p = \left(\frac{\vec{k}_\perp \times \vec{B} \cdot \vec{\kappa}}{k_\perp B} \right) \frac{\vec{k}_\perp \times \vec{B}}{k_\perp B^3} \cdot \left[\left(\frac{\sigma}{\tau} \right) \tilde{\nabla} P_\perp + \tilde{\nabla} P_\parallel \right] L^2, \quad (14)$$

where L is the equatorial L-shell distance. If $\alpha_p > 0$ the ballooning instability can occur with perturbation localized around the region where $\alpha_p > 0$.

By totally neglecting kinetic trapped particle pressures, the eigenmode equations are essentially MHD equations with anisotropic pressure along the ambient magnetic field line, and the MHD ballooning modes with symmetric Φ and $\delta B_\parallel$ structures along the north-south equilibrium magnetic field lines have the lowest beta stability threshold. The antisymmetric MHD modes have higher beta stability threshold. It has been shown [Cheng and Qian, 1993] that when the kinetic contribution from trapped particle pressures is included in the analysis, the symmetric ballooning modes are stabilized by the energetic trapped particle compressional effect in the absence of wave-particle resonance. On the other hand, the kinetic trapped particle effects on the stability of the

antisymmetric mode are vanishingly small. Therefore, the antisymmetric modes have the lowest critical beta threshold for ballooning-mirror instability. For small pressure anisotropy the antisymmetric MHD mode is a pure ballooning mode. But, for higher pressure anisotropy with simple mirror threshold ($\tau = 0$) exceeded at equator, the antisymmetric MHD mode becomes a hybrid mirror-ballooning mode with strong coupling between the transverse and the parallel magnetic field components.

Figure 1(a) shows the marginal stability boundaries of the antisymmetric ballooning-mirror mode in the equatorial $(\beta_{\parallel}, T_{\perp}/T_{\parallel})$ space for $\partial \ln P / \partial \ln L = -100, -50, -25, -10, -5, -2.5$, and -1 , respectively, where P is the pressure in the isotropic limit. The fixed parameters are $L = 6.6 R_E$ and azimuthal mode number $m = 50$. Also shown in Fig. 1(a) is the equatorial $\tau = 0$ curve above which the mirror instability criterion is satisfied at equator. The pressure anisotropy is destabilizing and can lower the critical beta for the ballooning-mirror mode. For $T_{\perp}/T_{\parallel} > 1.6$ (with $\partial \ln P / \partial \ln L = -5$) the critical beta is larger than the beta values that satisfy $\tau = 0$. For equatorial $(\beta_{\parallel}, T_{\perp}/T_{\parallel})$ values that are above the $\tau = 0$ curve, the mode has a dominant mirror mode characteristics. The marginal stability boundaries in the equatorial $(\beta_{\parallel}, T_{\perp}/T_{\parallel})$ space are very sensitive to the pressure gradient.

The marginal stability boundaries of the ballooning-mirror mode can also be given in terms of the equatorial values of α_p and τ . The corresponding stability boundaries are also shown in Fig. 1(b) in the equatorial (α_p, τ) space. Note that for $\tau < 0$, the α_p threshold is also negative, and we have plotted absolute value of α_p in Fig. 1(b) for $\tau < 0$. We note that the marginal stability boundary curves in (τ, α_p) space is very close to each other even for $10 > |\partial \ln P / \partial \ln L| > 0.1$. This probably holds even for different type of particle velocity distributions. This property is useful for comparing theoretical calculations with satellite observations where information on $\partial \ln P / \partial \ln L$ and particle velocity distribution is either unavailable or can not be obtained accurately. Therefore, we will employ τ and α_p parameters to compare theoretical ballooning-mirror instability thresholds with those obtained from satellite observed particle data where information on $\partial \ln P / \partial \ln L$ is either unavailable or can not be obtained accurately.

The field-aligned structure of the perturbed magnetic field of the antisymmetric mode changes from a pure ballooning mode with dominant transverse magnetic field component at $T_{\perp}/T_{\parallel} \approx 1$ to a mixed mirror-ballooning type mode with comparable transverse and compressional magnetic field components near the equator as $T_{\perp}/T_{\parallel}$ increase (or τ decreases). Figures 2(a) - (d) show the field-aligned perturbed magnetic field structure of the marginally stable antisymmetric mode along a marginal stability curve in the $(\beta_{\parallel}, T_{\perp}/T_{\parallel})$ space as shown in Fig. 8(a) with equatorial

values of (a) $T_{\perp}/T_{\parallel} = 1$, $\beta_{\parallel} = 1.93$ ($\tau = 1$), (b) $T_{\perp}/T_{\parallel} = 1.3$, $\beta_{\parallel} = 1.489$ ($\tau = 0.419$), (c) $T_{\perp}/T_{\parallel} = 1.6$, $\beta_{\parallel} = 0.987$ ($\tau = 0.052$), and (d) $T_{\perp}/T_{\parallel} = 2$, $\beta_{\parallel} = 0.575$ ($\tau = -0.149$). The fixed parameters are $L = 6.6$, azimuthal mode number $m = 50$, and $\partial \ln P / \partial \ln L = -5$. For positive values of τ , the local dispersion indicates a ballooning mode along the field line. As τ decreases, the amplitudes of the parallel magnetic field component $\delta B_{\parallel}$ and the azimuthal component δB_{ϕ} increase, and the mode also becomes more localized near the equator. At negative or small positive values of τ the theoretical ballooning-mirror mode structure resembles the field-aligned wave structures (all three perturbed magnetic field components) of the multisatellite (SCATHA, GOES2, GOES3, GEOS2) observations of a long lasting compressional Pc 5 wave event during November 14-15, 1979 [Takahashi et al., 1987; Takahashi, et al., 1990b]. This strongly suggests that this particular multisatellite observation may be related to the marginally stable ballooning-mirror mode with τ value close to zero.

3. Correlation Studies with Particle Data and Wave Events Observed by AMPTE/CCE

The AMPTE/CCE spacecraft was launched in August 1984 and was operated until early 1989. It had a perigee of $1.2 R_E$ geocentric, an apogee of $8.8 R_E$, an inclination of 5° , and an approximate orbital period of 16 hours. The satellite was spin stabilized with a spin axis maintained within 30° of the sun-Earth line. The spin period was approximately 5.9 sec.

The CCE magnetometer sampled 8 vectors/sec [Potemra et al., 1985]. Six-second median magnetic field record from CCE was plotted on microfiche for the time interval of August, 1984 to December, 1986 and were scanned for magnetic pulsations in the Pc 4-5 band (period = 45-600 s). We only selected events occurring near the dipole equator, because for these events it is easy to distinguish between waves of symmetric and antisymmetric field-aligned structures and also because near the equator the particle detector almost completely measured the particles trapped in the magnetic field. Four transverse wave events and six compressional wave events are selected and listed in Table 1. The distinction between compressional and transverse modes are made based on the relative magnitude of the field-aligned to the transverse components.

For each event in Table 1 we have analyzed particle data acquired with the ion charge-energy-mass spectrometer (CHEM). The CHEM instrument measures the energy and pitch angle distribution of all major ions in the magnetosphere [Gloeckler et al., 1985]. The energy coverage is from 0.3 keV/charge to 300 keV/charge. The pitch angle information is obtained by dividing the

scan plane (= spin equator of the satellite) into 32 sectors. Because the satellite spin axis was nearly perpendicular to the Earth's dipole field, the pitch angle coverage was nearly complete. A complete energy-pitch angle scan for a species is obtained at ~ 3 min intervals, and the particle pressure can be determined rather accurately in spite of the limited energy coverage [Lui et al., 1987; Lui and Hamilton, 1992]. CHEM measures particle flux of four major ion species H^+ , He^+ , He^{++} , and O^+ . In general the contribution of He^+ and He^{++} to the plasma beta is very small and can be neglected. The contribution of O^+ to the plasma beta can be as large as 30% of the total plasma beta during storm time and can be important in computing the parameters τ and α_p . However, due to low counting statistics the pitch angle distribution of O^+ is not well determined and is not used in computing τ and α_p [Cheng et al., 1994]. On the other hand, the pitch angle and energy distribution of H^+ is relatively well determined and were used to compute the parameters τ and α_p . In the present analysis we will neglect the O^+ contribution and retain only H^+ contribution. We will average the sectorized H^+ ion data over bins of $0.2 R_E$ width in the L shell distance.

The transverse wave events are typical radially polarized Pc 4 magnetic pulsations observed on the dayside during geomagnetically quiet times. During the period the transverse waves are observed, the proton betas are enhanced, but remain relatively small with $\beta_{||} \approx 0.05 - 0.25$, $\beta_{\perp} \approx 0.1 - 0.4$, and the pressure anisotropy parameter τ is close to unity with $\tau > 0.6$. The compressional wave events are selected from the 23 compressional Pc 5 wave events studied by Takahashi et al. [1987; 1990b]. As Takahashi et al. [1987] noted, very near the equator the transverse and the compressional components exhibit comparable amplitude with an occasional second harmonic in the compressional component. In comparison with the transverse wave events the period of the compressional waves is longer and their amplitude relative to the ambient field $\delta B/B$ is larger. During the period that there is no wave activity the plasma betas are usually less than one. But, when the compressional waves are observed, the plasma betas are greatly increased and become larger than one with $\beta_{||} \approx 1 - 5$, and the pressure anisotropy parameter τ is somewhat small and can become negative with $\tau < 0.6$ ($P_{\perp}/P_{||} \approx 1.1 - 1.5$).

In Fig. 3 we plotted the values of τ and α_p computed from the AMPTE/CCE particle data separately during (a) the transverse wave events and (b) the compressional wave events listed in Table 1. Also plotted in Fig. 3 are the marginal stability boundary curves of the antisymmetric $\delta B_{||}$ ballooning-mirror instability numerically computed for a local bi-Maxwellian velocity distribution with the pressure gradient in the range of $100 > |\partial \ln P / \partial \ln L| > 1$. The observation points in the (τ, α_p) space were calculated for the period listed as "Data Interval" in Table 1. The symbol "o" represents compressional wave events, and the symbol "+" represents the transverse wave

activities. When there is no wave activity the values of τ and α_p tend to be well below the ballooning-mirror thresholds. The transverse and the compressional wave events clearly occupy different domains in the (τ, α_p) space. For the compressional wave events the values of τ and α_p are either near or above the theoretical marginal stability boundary curves of the antisymmetric $\delta B_{\parallel}$ ballooning-mirror modes. The compressional wave events tend to occur when $\tau \leq 0.6$ and $O(10) \leq \alpha_p \leq O(10^3)$. Thus, the compressional waves are probably related to hybrid ballooning-mirror modes excited when the pressure gradient, the plasma beta, and the pressure anisotropy ($P_{\perp}/P_{\parallel}$) are large. The transverse wave events tend to occur when τ is close to 1 and $0 < \alpha_p \leq O(10)$ which are about one order of magnitude below the theoretical ballooning-mirror instability thresholds for antisymmetric $\delta B_{\parallel}$ mode. Thus, the transverse waves are probably related to resonant type ballooning instabilities such as the drift Alfvén ballooning mirror instability [Chen and Hasegawa, 1991] that can be excited at lower plasma beta and pressure anisotropy.

4. Summary and Discussion

In the paper we have presented a kinetic-MHD eigenmode stability study of the ballooning-mirror mode for anisotropic pressure plasmas in a dipole magnetic field. The eigenmode equations take into account the coupling of the transverse and compressional components of the perturbed magnetic field. The symmetric modes are stabilized by the energetic trapped particle kinetic effect in the absence of wave-particle resonance. The stabilization results from the fact that the hot trapped particles precess very rapidly across the $\vec{B}$ field, their motion becomes very rigid with respect to low frequency MHD perturbations with symmetric structure of parallel perturbed magnetic field $\delta B_{\parallel}$ and electrostatic potential Φ along the north-south ambient magnetic field, and thus they do not contribute to the destabilizing pressure gradient to drive ballooning instability. On the other hand, the energetic trapped particle's rapid bounce motion tends to average out the nonadiabatic pressure contribution associated with the antisymmetric wave structure in a bounce period. Therefore, the antisymmetric mode is only weakly influenced by energetic trapped particle kinetic effects and has the lowest critical beta threshold mainly determined by MHD theory.

Based on a local bi-Maxwellian velocity distribution, the stability of the ballooning-mirror mode is numerically computed and is expressed in terms of parallel plasma beta $\beta_{\parallel}$ and temperature ratio $T_{\perp}/T_{\parallel}$ at equator. The field-aligned perturbed magnetic field structure of the antisymmetric mode changes from a ballooning mode with dominant transverse magnetic field component at $T_{\perp}/T_{\parallel} = 1$ ($\tau = 1$) to a hybrid mirror-ballooning mode with comparable transverse and compressional magnetic field components near the equator as $T_{\perp}/T_{\parallel}$ increases (i.e., τ decreases).

As τ decreases, the amplitudes of the parallel magnetic field component $\delta B_{\parallel}$ and the azimuthal component δB_{ϕ} increase, and the mode also becomes more localized near the equator. In fact, at negative or small positive values of τ the theoretical eigenmode structure resembles the field-aligned wave structure (all three perturbed magnetic field components) of the multisatellite (SCATHA, GOES2, GOES3, GEOS2) observations of a long lasting compressional Pc 5 wave event during November 14-15, 1979 [Takahashi et al., 1987; Takahashi, et al., 1990b]. This suggests that this particular multisatellite observation may be related to the marginally stable ballooning-mirror mode with τ value close to zero.

From the AMPTE/CCE particle and magnetic field data observed during Pc 4-5 wave events we have computed the instability parameters and performed a correlation study with the theoretical ballooning-mirror instability threshold parameters in the (τ, α_p) space so that close comparison with the theoretical instability thresholds can be made. The particle data were acquired with the ion charge-energy-mass spectrometer (CHEM). The CHEM instrument measures the energy and pitch angle distribution of all major ions in the magnetosphere. The energy coverage is from 1 keV/charge to 300 keV/charge (fluxes below 1 keV are unreliable), and the pitch angle coverage was nearly complete. The transverse and the compressional wave events are found to occupy different domains in the (τ, α_p) space. The transverse wave events tend to occur when τ is close to 1 and $0 < \alpha_p \leq O(10)$. The compressional wave events tend to occur when $\tau \leq 0.5$ and $\alpha_p \geq O(10^2)$. The results of the correlation studies are consistent with the theory of ballooning-mirror instabilities. Therefore, the transverse wave is related to the ballooning mode at lower beta. The compressional wave is related to a mixed ballooning-mirror mode excited when pressure gradient and pressure anisotropy ($P_{\perp}/P_{\parallel}$) are large.

It is perhaps not surprising that the internally driven Pc 4-5 waves are related to the MHD type ballooning-mirror instabilities because these Pc 4-5 waves are usually not of bursty type. A resonant type instability tends to have bursty behavior in time because as soon as the resonant particles release their energy and are scattered out of resonance with the wave, the wave will be damped by other resonant particles that takes energy from the wave. On the other hand, an MHD type instability is destabilized by the fluid free energy and is weakly resonating with all particle species. After the fluid free energy is released, the wave become nearly marginally stable due to very weak resonant damping and can survive for a very long period of time. We also note that long period compressional Pc 5 waves are usually observed during recovery phase of a substorm. The substorm recovery time is roughly the time it takes to stabilize the compressional Pc 5 waves by transporting or dissipating excess hot ring ion pressure out of the ring current region.

One of the future efforts will be to explore new satellite data of ring particle distribution as input to the self-consistent equilibrium calculation presented. One possibility is to gather data from all ion instruments on board AMPTE/CCE which cover an energy range of 1-600 keV and a nearly full range of pitch angle.

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Table 1
List of Selected Wave Events

Year	Day	Data Interval, UT		MLAT Range, degrees		Event Interval, UT		Wave Mode
84	245	0900	1100	1	3	0930	1030	Transverse
84	251	2130	2330	-1	1	2150	2300	Transverse
85	324	2140	2340	0	2	2200	2310	Transverse
86	339	1510	1740	-5	-1	1650	1740	Transverse
85	256	1700	1900	-4	1	1740	1830	Compressional
85	259	0100	0500	-3	2	0300	0400	Compressional
85	263	0100	0400	0	4	0130	0250	Compressional
85	278	0000	0500	-3	4	0300	0500	Compressional
85	284	0320	0610	0	3	0350	0540	Compressional
85	286	1500	1900	-3	6	1630	1750	Compressional

Figure Captions

Fig. 1 (a) The marginal stability boundaries of the antisymmetric ballooning-mirror mode in the equatorial $(\beta_{\parallel}, T_{\perp}/T_{\parallel})$ space for $\partial \ln P / \partial \ln L = -100, -50, -25, -10, -5, -2.5$, and -1 , respectively, with the fixed parameters: $L = 6.6 R_E$ and azimuthal mode number $m = 50$. The equatorial $\tau = 0$ curve is also shown. (b) The same stability boundaries are shown in the equatorial (α_p, τ) space. Note that for $\tau < 0$, the α_p threshold is also negative and absolute values of α_p for $\tau < 0$ are plotted.

Fig. 2 The field-aligned perturbed magnetic field structures of the marginally stable antisymmetric modes along a marginal stability curve in Fig. 8(a) with equatorial values of (a) $T_{\perp}/T_{\parallel} = 1$, $\beta_{\parallel} = 1.93$ ($\tau = 1$), (b) $T_{\perp}/T_{\parallel} = 1.3$, $\beta_{\parallel} = 1.489$ ($\tau = 0.419$), (c) $T_{\perp}/T_{\parallel} = 1.6$, $\beta_{\parallel} = 0.987$ ($\tau = 0.052$), and (d) $T_{\perp}/T_{\parallel} = 2$, $\beta_{\parallel} = 0.575$ ($\tau = -0.149$). The fixed parameters are $L = 6.6 R_E$, azimuthal mode number $m = 50$, and $\partial \ln P / \partial \ln L = -5$.

Fig. 3 The values of τ and α_p computed from the AMPTE/CCE particle data separately for (a) the transverse wave events and (b) the compressional wave events listed in Table 1. Also plotted are the marginal stability boundary curves of the antisymmetric $\delta B_{\parallel}$ ballooning-mirror modes numerically computed for a local bi-Maxwellian velocity distribution with the pressure gradient in the range of $100 > |\partial \ln P / \partial \ln L| > 1$.

Fig.1

Fig.2

Fig.3

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