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SHELL DISTRIBUTION INSTABILITY UPSTREAM TERRESTRIAL BOW SHOCK

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Abstract. It is shown that the stability of isotropic ion shell distribution upstream terrestrial bow shock, previously obtained in the framework of MHD approximation, is violated at finite ion Larmor radius (FLR) wavelengths. The new instability that results in the growth of compressional mode due to FLR effect is found in the upstream region. A general dispersion relation as well as a growth rate for the most growing perturbations is obtained. The results of the theory are applied to interpretation of existing satellite data.

1. Introduction

It is of common knowledge that the ion velocity distributions in space plasmas considerably deviate from the canonical Maxwellian form. For example, in the upstream region the ion distribution is characterized by two distinct populations, a core plasma of solar wind origin and an additional nearly isotropic, diffuse suprathermal ions, the ion halo. The latter could be accelerated by either the Fermi or the shock-drift mechanisms [e.g., Paschmann et al., 1979; for reviews see also Thomsen, 1985; and Scholer, 1985]. The halo is the result of the formation of the so-called quasi-linear plateau that is produced in the pitch-angle diffusion that arises in the course of the ion-cyclotron interaction of the solar wind with Alfven waves. The concrete shape of the halo substantially depends on the angle between the normal to the shock front and the ambient magnetic field. In the locally quasi-perpendicular shocks the distribution of the ions along the magnetic field has the form of the ion beam whereas in the quasi-parallel shocks the typical velocity distribution is the diffuse shell or halo. It is customary to consider that halo is stable, i.e. it does not radiate waves. The present paper revisits the fully kinetic theory of mirror type waves in high-β plasma taking into consideration both non-Maxwellian distributions and finite ion Larmor radius (FLR) effects. It is demonstrated that in the anisotropic high-β plasmas apart from the classical mirror instability (MI) the general dispersion relation for low-frequency waves admits for instability that arises even when plasma is mirror stable. This new instability is termed ``halo instability'' (HI). Similar to the classical MI the HI is feeded by resonant interaction of the low-frequency mode with ions possessing very small parallel velocities. The key element of the instability mechanism refers to the non-monotonic dependence of the ion velocity distribution that serves as the source of free energy. One may expect that this instability may become important in the generation of low frequency compressional waves upstream of the Earth's bow shock that is occasionally observed by satellites.

2. Instability of shell velocity distribution

In isotropic high-β plasma the MS waves are described by the following dispersion equation

$$\varepsilon_{22} - N^2 = 0\,, \tag{1}$$

where ε_{22} is the component of the dielectric tensor given by

$$\varepsilon_{22} = 1 + \sum_j \frac{q_j^2 \omega_{cj}^2}{\varepsilon_0 m_j \omega^2 k_\perp^2} < \frac{G\xi^2 J_1^2}{\omega - k_\parallel v_\parallel} > - \sum_j \frac{2q_j^2}{\varepsilon_0 m_j \omega^2 k_\perp^2} < G\xi^2 (\omega - k_\parallel v_\parallel) J_1'^2 > . \tag{2}$$

Here $N^2 = k^2 c^2 / \omega^2$ is the square of the refractive index, q_j is the particle charge of the jth specious (it takes the value $q_e = -e$ for the electrons and $q_i = e$ for the ions), the summation is carried out over all particle kinds (electrons and ions), the angle bracket <…> denotes the averaging over all particle kinds, ε_0 is the permittivity of free space, $k_{\parallel(\perp)}$ is the parallel (perpendicular) component of the wave vector $\mathbf{k}$, $J_1(\xi)$ is the Bessel function of the first order, c is velocity of light, ω is the wave frequency, m_j is the particle mass of the jth kind, k is the wave number, $\xi = k_\perp v_\perp / \omega_{cj}$, and ω_{cj} is the particle cyclotron frequency of the jth kind. All perturbed quantities are considered to vary as $\propto \exp(-i\omega t + i\mathbf{k}\cdot\mathbf{r})$. The operator G is given by

$$G = (\omega - k_\| v_\|)\frac{\partial F_j}{v_\perp \partial v_\perp} + k_\| \frac{\partial F_j}{\partial v_{II}} \tag{3}$$

The tensor component ε_{22} consists of two parts corresponding to the solar wind plasma and the ion halo, respectively.

$$\varepsilon_{22}^{sw} = \frac{c^2}{c_A^2}\left(1 - \frac{k_\perp^2 v_{Ti}^2}{\omega^2}\right) \quad \text{and} \quad \varepsilon_{22}^{h} = \frac{4i\pi^2 c^2 \omega_{ci}^2}{\omega k_\| c_A^2}\frac{n_h}{n_i}\mathrm{I} \tag{4}$$

where v_{Ti} is the solar wind thermal velocity, n_h and n_i are the halo and solar wind number densities, respectively, and parameter I is given by

$$\mathrm{I} = \frac{\int_0^\infty (J_1^2 + \xi J_1 J_1')F_i v dv}{< F_i >} \tag{5}$$

Substituting expression (4) into Eq. (1) one finds dispersion relation for the halo instability

$$\omega^2 = k^2(c_A^2 + \sin^2\theta v_{Ti}^2) - \frac{4i\pi^2 c^2 \omega_{ci}^2 \omega}{k_\| c_A^2}\frac{n_h}{n_i}\mathrm{I} \tag{6}$$

Decomposing Eq. (6) into its real and imaginary parts one finds

$$\mathrm{Re}\,\omega = k(c_A^2 + \sin^2\theta v_{Ti}^2)^{1/2} \quad \text{and} \quad \mathrm{Im}\,\omega = \gamma = -\frac{2\pi^2\omega_{ci}^2}{k_\|}\frac{n_h}{n_i}\mathrm{I} \tag{7}$$

One sees that instability arises if $\int_0^\infty (J_1^2 + \xi J_1 J_1')F_i dv < 0$. In order to obtain quantitative estimations we choose a simplified velocity distribution for the ion halo in the form of a delta-function

$$F = \frac{n_h}{4\pi v_0^2}\delta(v - v_0) \tag{8}$$

where v_0 is the halo velocity. Then

$$\frac{\gamma^{\max}}{\omega_R} \approx 0.1\frac{n_h}{n_i}\frac{1}{k_\| \rho_i} \tag{9}$$

The plasma is unstable if the halo velocity satisfies the condition $3.8\omega_{ci}/k_\perp > v_0 > 2.4\omega_{ci}/k_\perp$. The maximum growth rate is attained at $k_\perp = k_\perp^{\max} = 3.1\omega_{ci}/v_0$

The analysis presented above shows that upstream region, where plasma consists of two components, relatively cold background of the solar wind origin and the ion halo can be unstable under generation of the compressional mode. The generation arises when the halo velocity is relatively large and lies in the range $3{,}8\omega_{ci}/k_\perp > v_0 > 2{,}4\omega_{ci}/k_\perp$. The instability leads to the halo gradual cooling. We note that for the instability it is necessary that the ratio of the wavelength to the ion Larmor radius of the ion halo should take the finite value. The growth of the wave amplitude will continue until the effects due to dispersive spreading of the wave packet starts to play a game. The balance of dispersion and nonlinearity may lead to the appearance of stationary solitary waves, the solitons. It should be mentioned that the sign of the dispersion of the fast magnetosonic waves depends on the details of the velocity distribution In particular, in Maxwellian plasma it is negative, i.e. the wave phase velocity decreases with the growth in the wave number. For such dispersion the stationary solution takes the form of the "bright" solitons. This differs from that due to the nonlinear development of diamagnetic (mirror) which terminated by the formation of the deep magnetic field dropouts.

3. Discussion and Conclusions

We presented a fully kinetic local analysis of low-frequency oscillations in a high-β non-Maxwellian plasmas accounting for the FLR effect. The general low-frequency dispersion relation of such plasma admits two different types of plasma instabilities. The first one corresponds to the classical MI that arises when generalized plasma anisotropy exceeds the inverse perpendicular plasma beta. Another type of instability develops even when plasma is mirror stable and the mirror force is weak or vanishes totally. In this case the instability arises if the ion distribution function possesses a halo on its tail. It could only be revealed by taking into consideration the FLR effects. Hence, it is the regions in space where halo distribution functions are observed where the new instability will occur. Such conditions are regularly realized in the foreshock region upstream of the Earth's parallel bow shock. Ion distributions observed here have been found to consist of the core solar wind plasma with an admixture of a diffuse nearly isotropic suprathermal ion population which when fully developed forms a ring or shell around the core. Conditions like these will satisfy the instability criterion and cause the low-frequency modes to grow. Here we have given only the criterion for the occurrence of instability. The wave properties will be investigated elsewhere. Concerning the identification of the waves simultaneous 4-point measurements like those which the Cluster mission can provide will have the potential of deciding whether the observed low-frequency modes have been excited in the conventional way or by the newly discovered instability. These observations are well suited for determination of the spatial scales when the spacecraft are at smallest separation. So far the gross agreement with the kinetic theory presented here has been provided by the observations. They are, however, restricted to long-wavelength modes and large wave amplitudes only, the latter indicating that the modes were observed in their nonlinear state to which the present theory only marginally applies.

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References

Paschmann, G., N. Sckopke, S. J. Bame, J. R. Asbridge, J. T. Gosling, C. T. Russell, and E. W. Greenstadt, Association of low-frequency waves with suprathermal ions in the upstream solar wind, Geophys. Res. Lett., 6, 209, 1979.

Scholer, M., Diffusive Acceleration, In: “Collisionless Shocks in the Heliosphere: Reviews of Current Research”, Geophysical Monograph, American Geophysical Union, Washington D.C., vol. 35, 287, 1985.

Thomsen, M. F., Upstream Suprathermal Ions, In: “Collisionless Shocks in the Heliosphere: Reviews of Current Research”, Geophysical Monograph, American Geophysical Union, Washington D.C., vol. 35, 253, 1985.