Field-aligned and Gyrating Ion Beams in a Planetary Foreshock

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Abstract. The foreshock region is the first signature of the interaction of the solar wind with a planet's plasma environment when approaching its collisionless bow shock. Part of its structure and dynamic is determined by instabilities, which are created by the interaction of the solar wind with backstreaming ion populations. The interaction of the reflected ions with the solar wind drives ion/ion beam instabilities, which generate waves that are then convected towards the shock by the solar wind. Subsequently they may mediate the shock structure and its reflection properties. The most well-know examples are the field aligned ion beams (FABs), produced by reflection processes in the quasi-perpendicular and oblique regions of the shock. Other prominent examples are the gyrating ions with well-defined pitch-angle and gyrophase organization around the local magnetic field observed downstream of the FABs region. These gyrophase-bunched ions are always associated with large amplitude quasi-monochromatic right-hand mode low-frequency waves. Different mechanisms have been put forward to explain these ion features. This paper will discuss recent advances on this topic from multi-spacecraft observations (Cluster) as well as theoretical considerations.

Keywords: Planetary bow shock, ion foreshock, wave-particle interaction.
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1. INTRODUCTION

Several types of ion populations have been observed upstream of the Earth's bow shock and these population have been extensively studied and hypotheses have been put forward to explain their origin [1, and references therein]. Ion beams of several keV collimated along interplanetary field lines have been observed upstream from the quasi-perpendicular shock. Downstream of the field-aligned beam region, distributions characterized by a gyromotion around the magnetic field, *i.e.* a non-vanishing perpendicular bulk velocity with respect to the background magnetic field, have been reported. These gyrating ion distributions are nongyrotropic or nearly-gyrotropic. Numerous studies concerning gyrating ions have been reported in earlier investigations mainly from ISEE 1 and 2 [2,3,4,5,6,7], AMPTE [8] and WIND [9,10,11]. Gyrating ions are often observed in association with ULF waves having substantial amplitude [7]. The waves are right-handed and propagate nearly along the ambient magnetic field [4,9,10,11]. It is believed that the ULF waves are excited

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through a beam plasma instability resulting from the propagation of field-aligned ions which precede them closer to the foreshock boundary [12]. The produced waves can in turn trap the ions and cause the phase bunching of the distribution in what is called a beam disruption mechanism [13].

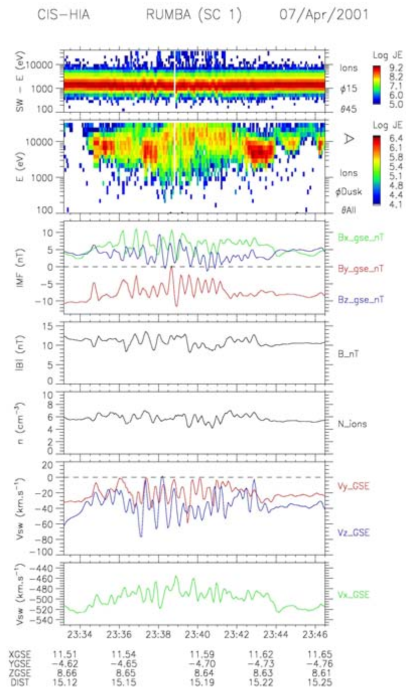
2. PREVIOUS OBSERVATIONS

A quantitative analysis of particle and monochromatic waves was made from ISEE data [6] which strongly suggested that there was a coherent wave-particle interaction. They obtained a phase relationship between the gyrovelocity $\mathbf{v}_\perp$ and the transverse wave field $\delta\mathbf{B}_\perp$ so that energy transfer occurred between the particles and the waves and gyrophase trapping by the wave was possible. Since the field-aligned beams propagate into regions deep within the foreshock, the local production of gyrating ions through this process should be observed very far from the shock contrary to directly shock-produced gyrating ions which are subject to rapid gyrophase-mixing [14]. First observations of several gyrating ion distributions and their association with low frequency waves at distances larger than 20 R_E from the shock were reported from WIND data [9] . There was again a clear indication of coherent wave-particle interaction. A more detailed study of the three-dimensional ion distributions with a large data set and the highest available time resolution (3s) has shown that these observational features can be found up to more than 80 R_E from the shock [11]. An investigation of the non-linear wave trapping mechanism has shown that it can explain the properties of such gyrating ion distributions registered at large distances from the shock [10]. It has been shown that the particles are not only bunched in gyrophase but also trapped in pitch-angle in velocity space around a value which is directly related to the amplitude of the wave self-consistently generated by the original field-aligned ion beam.

3. CLUSTER OBSERVATIONS

This local production mechanism has been recently investigated to explain the existence of well-defined gyrating ion distributions reported from the Cluster CIS measurements in the Earth’s foreshock [15]. One example is displayed on Figure 1. For this event, Cluster s/c 1 was connected to the bow shock, during a much larger interval. At 2334:30 UT, energetic ions are revealed in the second energy spectrogram corresponding to measurements by the High side of the HIA instrument (the difference with the first panel showing the solar wind population is quite obvious). High fluxes are then continuously observed until 2344 UT, followed by two small patches. These ions are mostly propagating sunward, as revealed from the analysis of their guiding center velocities, i.e. they are backstreaming ions. Before 2334:30 UT, the IMF was nearly quasi-steady.

Conversely, prominent large amplitude low frequency waves are observed after 2335:45 UT both on the magnetic field and on the solar wind velocity. Figure 2 displays three-dimensional 4-s representation of the ion distribution functions registered by CIS-CODIF. Nine consecutive distributions are shown for one energy channel (~8 keV) for which the observed backstreaming fluxes are maximum for a time interval inside the event displayed on Figure 1. Each frame in Figure 2 is a projection in gyrophase and pitch-angle with the **B**-direction located at the center.



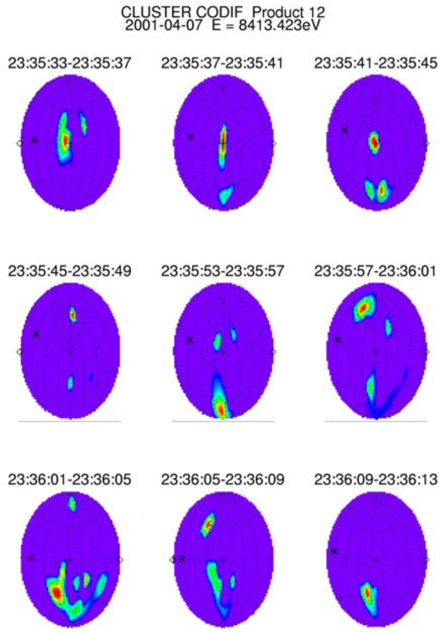


FIGURE 1. Observations from CLUSTER CIS and FGM on satellite 1 between 23:33-23:46 UT on April 7, 2001 : energy-time spectrograms of all ions from CIS/HIA for "solar wind sectors" (sunward looking direction - upper panel) and "dusk" solid angle (duskward looking direction - second panel), respectively; dc magnetic field components in GSE coordinates and its magnitude; ion density and bulk velocity in GSE coordinates derived from HIA measurements.

FIGURE 2. Fig. 2. Sequence of consecutive three-dimensional 4-s display of the proton angular distributions registered by CIS-CODIF for an energy of ~8 keV (flux maximum). Each frame represents the normalized distribution function on a surface of constant energy in the solar wind frame of reference projected to display 4π-coverage. The $\mathbf{B_0}$ vector is located at the center of each plot (background field shown by a '+'identical for all frames) and the '*' sign indicates the solar wind direction. For each frame, the maximum value of the normalized phase space density is shown in red.

The three first snapshots indicate an ion beam propagating along the +**B** direction with a parallel velocity of 1,100 km/s but the third one also shows a second peak for a large pitch-angle of about 60°. Then after 2335:45, the spacecraft has entered a gyrating ion region. Gyrating ions are identified by their gyrophase-restricted distribution peaked off the magnetic field direction. The interplanetary magnetic field used to plot the distributions is averaged over the spin interval (4 seconds) while the local proton cyclotron period is 7 seconds (i.e., about two ion sampling intervals). The gyrating distributions show a clear rotation of their maximum phase density in the left-handed sense around the magnetic field with alternating values separated by about 180°. Such gyrating ion distributions are observed up to ~2344 UT.

4. WAVE-PARTICLE INTERACTION

Using multi-spacecraft analysis techniques [*e.g.*, 16], the properties of large amplitude low frequency waves associated with the gyrating ion distributions have been analyzed by [15]. The waves are right-hand mode waves ('30-s waves'). They have shown that these wave are in cyclotron resonance with the field-aligned beam observed just before the spacecraft entered the gyrating ion/ULF wave region. This is the first direct quantitative evidence so far of this cyclotron resonance from observations in the ion foreshock. Then, they have studied the possibility of resonantly driving these waves unstable from the electromagnetic ion/ion beam instability by field-aligned beam ions also observed in the same region. The results from the linear theory has lead to a very good agreement with the observed wave mode.

The gyrating feature of the ion distribution is inconsistent with a specular reflection at the Earth's bow shock since the observed pitch-angles of the gyrating ions are much too large (it should be nearly θ_{Bn} [*e.g.*, 17], which here has been found to be close to 30°). It is thus necessary to invoke a local production mechanism for these upstream distributions. For this, we make some theoretical considerations about the nonlinear trapping of ions by a monochromatic electromagnetic wave. From the equation of motion of a particle of velocity **v** in the frame moving along the dc magnetic field $\mathbf{B_0}$ (//z) at the phase velocity V_ϕ (<<c) of a monochromatic wave, propagating along $\mathbf{B_0}$ with a constant amplitude B_1, it is easy to deduce two constants of the motion [*e.g.*, 18,19,20,21]:

$$T = w_{//}^2 + w_\perp^2 = C_1 \quad (1)$$

$$S = (w_{//} - 1)^2 - 2\frac{\Omega_1}{\Omega_0} w_\perp \sin\psi = C_2 \quad (2)$$

where $\mathbf{w} = \frac{k_{//}}{\Omega_0}\mathbf{v}$, $\Omega_{0,1} = \frac{qB_{0,1}}{m}$, $\psi = \varphi + k_{//} z$

and φ is the gyrophase angle. The invariance of T is simply the conservation of total particle energy in the wave frame (no electric field in this frame). The invariant S relates the parallel and perpendicular motion of the particles. Using the particle equations of motion with (4) and (5), it is possible to show that S can be used as a Hamiltonian of the particle motion and that the system is solvable by a quadrature

$$\frac{dw_{//}}{dt} = \pm\frac{\Omega_0}{2}\sqrt{4\left(\frac{\Omega_1}{\Omega_0}\right)^2 \sin^2\psi (C_1 - w_{//}^2) - \left[(w_{//}-1)^2 - C_2\right]^2} \quad (3)$$

which can be solved in terms of elliptic integrals as for a pendulum equation. The particle is thus trapped in a potential well. Using the pitch-angle α such as $\tan\alpha = w_\perp / w_{//}$, the equations of motion

$$\frac{d\alpha}{dt} = -\delta\cos\psi \quad \text{and} \quad \frac{d\psi}{dt} = \delta\cot\alpha\sin\psi + \sqrt{T}\cos\alpha - 1, \quad \text{where } \delta = \frac{\Omega_1}{\Omega_0} = \frac{\delta B_\perp}{B_0} \quad (4)$$

can be derived from the Hamiltonian $S(\alpha,\psi)$.

This Hamiltonian has a singularity for $\psi_0 = \pi/2$ which is the only to be considered since the pitch angle α is defined in the interval [0 π]. As a first step, we consider a mono-energetic parallel ion beam, i.e. this means from equations (2), (4) and (6) that we have T=1. Then, by linearizing the trapping potential, around $\psi_0 = \pi/2$, it is straightforward to show that this singularity corresponds to a value α_0, defining the center of the trapping cells [for small values of α_0, it is possible to use the approximation $\alpha_0 \approx (2\delta)^{1/3}$]. If $V_{//0}$ is the initial velocity of the cyclotron resonant beam (i.e., T=1), the nonlinear interaction will tend to create a peak in the distribution around the center of the trapping cell in phase space associated with the pitch angle α_0.

We have derived the experimental parallel and perpendicular velocities for some observed gyrating ion distributions corresponding to the time intervals where we have analyzed the low frequency waves. Then we have computed the associated pitch-angles in the wave frame (using the experimental wave phase speed). To illustrate this, for the event described above, the experimental pitch-angle is $\alpha_{o\exp}=60\pm5°$ while the theoretical value is $\alpha_{otheory}=59.8°$ using the mean value $\delta=0.85$ from the observations**.** The very good agreement obtained strongly suggests the possible scenario that the quasi-monochromatic wave generated from the ion/ion beam instability could then have non-linearly trapped the ions to produce the resulting gyrating distributions.

5. CONCLUSIONS

The possibility of producing the observed gyrophase-bunched ion distributions from the disruption of the beam by the excited wave has led to a good quantitative agreement from a nonlinear trapping theory which predicts that the pitch-angle of the final gyrating ion distribution is related to the wave amplitude [10]. This result is very similar to those obtained from previous studies in the distant foreshock (up to 80 R_E) from WIND data with lower backstreaming ion densities and wave amplitude [9,10], which could mean that the present case study corresponds to the same mechanism observed by Cluster closer to the bow shock. Other gyrating ion events have been identified in the Cluster data [22]. Most appear consistent with this trapping mechanism while only one event with gyro-phased bunched ions produced by specular reflection at the bow shock surface has also been identified [17].

The analytical test-particle calculations of the nonlinear interaction between a field-aligned beam and the single self-generated cyclotron-resonant wave briefly described here cannot tell anything about the physical description during the wave growth. Numerical simulations are necessary for that. A previous study [13] led to pitch-angle diffusion though the production mechanism of gyrophase-bunched ion distributions is a coherent process and not a diffusive one. It would be therefore strongly necessary to conduct new numerical kinetic simulations to better understand this trapping process. It could help to quantify the life-time of the gyrophase-bunched distribution and compare it with observations.

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