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Nonlinear wave-particle interaction upstream from the Earth's bow shock

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Abstract. Well-defined ring-like backstreaming ion distributions have been recently reported from observations made by the 3DP/PESA-High analyzer onboard the WIND spacecraft in the Earth's foreshock at large distances from the bow shock, which suggests a local production mechanism. The maximum phase space density for these distributions remains localized at a nearly constant pitch-angle value for a large number of gyroperiods while the shape of the distribution remains very steady. These distributions are also observed in association with quasi-monochromatic low frequency (~ 50 mHz) waves with substantial amplitude ($\delta B/B > 0.2$). The analysis of the magnetic field data has shown that the waves are propagating parallel to the background field in the right-hand mode. Parallel ion beams are also often observed in the same region before the observation of both the ring-like distributions and the waves. The waves appear in cyclotron resonance with the ion parallel beams. We investigate first the possibility that the ion beams could provide the free energy source for driving an ion/ion instability responsible for the ULF wave occurrence. For that, we solve the wave dispersion relation with the observed parameters. Second, we show that the ring-like distributions could then be produced by a coherent nonlinear wave-particle interaction. It tends to trap the ions into narrow cells in velocity space centered on a well-defined pitch-angle, directly related to the saturation wave amplitude in the analytical theory. The theoretical predictions are in good quantitative agreement with the observations.

1 Introduction

The WIND spacecraft carries several experiments allowing to investigate the Earth's foreshock region up to distances larger than those studied by ISEE and AMPTE, providing the opportunity to study the upstream populations, the wave activity and their association at large distance from the bow shock. Moreover this gives an opportunity to investigate the evolution of the backstreaming ion distribution functions away from the shock. Among the several types of foreshock ion distributions which have been identified and studied up to now (e.g., Fuselier et al., 1994), gyrating ion distributions are characterized by a non-vanishing perpendicular bulk velocity with respect to the background magnetic field (Thomsen et al., 1985; Fuselier et al., 1994). These gyrating ions exhibit two types of behavior whether their distribution function exhibits phase bunching features or not. The gyrophase-bunched ions have been observed in the overall region probed by the ISEE spacecraft (up to 10-15 R_E from the bow shock), whereas the nearly-gyrotropic distributions (or ring-beam) are rarely observed beyond 4 R_E from the shock (Fuselier et al., 1994). Meziane et al. (1997) reported the first observations from the WIND 3DP/PESA-High instrument (Lin et al., 1995) of several gyrating ion distributions and their association with low frequency waves, at distances larger than 20 R_E from the shock. There was a clear indication of wave-particle interaction. More recently a detailed study of the three-dimensional ion distributions with a much larger data set and the highest available time resolution has shown that these observational features can be found up to more than 80 R_E from the shock (Meziane et al., 2000). This strongly suggests seeking for a local production mechanism for these backstreaming ion distributions.

This paper is structured as follows: in section 2, we illustrate the observations on particle and low frequency waves by describing one of the reported event; in section 3 we discuss the possibility of wave-particle interaction through cyclotron resonance of the local ion distributions; in section 4 we investigate the free energy source for driving an ion/ion instability and solve the linear dispersion relation; in section 5, we discuss a coherent nonlinear wave particle process as a local source mechanism for producing the ring-like distribution; section 6 is devoted to conclusions.

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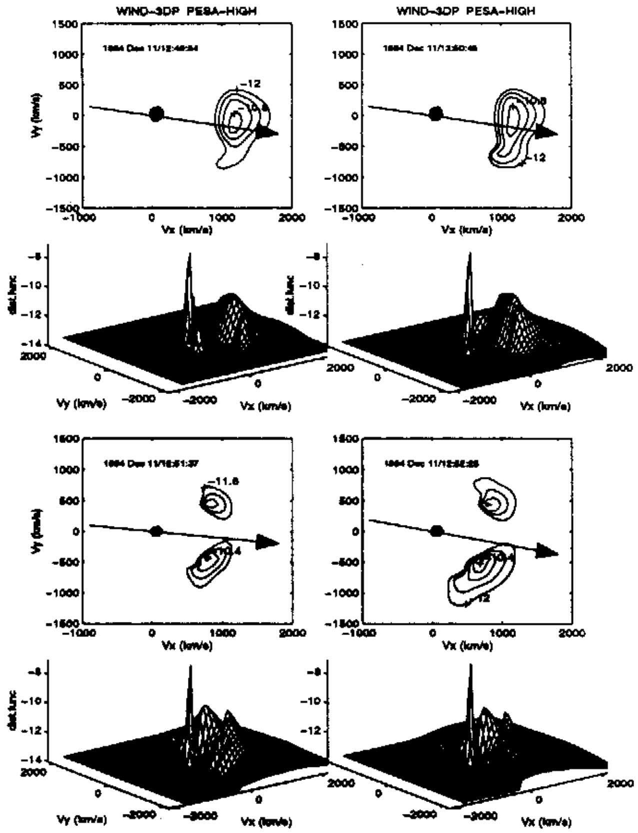

Fig. 1. Sequence of four consecutive ion distributions registered by the WIND 3DP/PESA-H instrument in the Earth's foreschock on December 11, 1994 around 1250 UT. For each distribution the upper part displays the contour plots in the Vx-Vy plane of the GSE system in the solar wind reference frame. The arrow gives the projection of the IMF direction, which nearly lies in the ecliptic plane, and the lower part displays the phase space density in the Vx-Vy plane of the GSE system.

2 Observations

2.1 Gyrating ion distributions

Figure 1 adapted from Meziane et al. (1997) displays examples of backstreaming ion distributions registered by the WIND 3DP/PESA-High instrument in the Earth's foreschock on December 11, 1994 around 12:50 UT, while the spacecraft was at $\sim$22 R_E from the bow shock. For each time, the upper panel shows contour plots associated with the backstreaming ions moving in the sunward direction in the V_X-V_Y plane of the Geocentric Sun Earth (GSE) system (with x pointing toward the sun and z toward the north pole of the ecliptic) in the solar wind reference frame (the contour plots around zero velocity correspond to residual solar wind distribution, see Meziane et al. (1997) for more details). The arrow gives the projection of the interplanetary magnetic field (IMF) direction, which nearly lies in the ecliptic plane during the entire event. The lower panel displays the phase space density in the V_X-V_Y plane. The two first distributions appear as field-aligned beams while for the two last from 12:51:37 UT, the cut of the distribution in the V_X-V_Y plane appears nearly symmetrical about the mean magnetic field direction. This suggests that this suprathermal ion component be torus-like shaped around the background field direction, appearing as a "gyrotropic" distribution. The detailed 3D observations confirm this characteristic. Such a distribution is not observed only sporadically but appears steadily from one sampling interval to another: the ring-like feature then remains observed over at least 20 proton cyclotron periods ($\tau_{cy} \sim 10$ s). This indicates temporal stability of the distribution (while the spacecraft is basically in the rest reference frame) or at least its permanent refreshment by some mechanism.

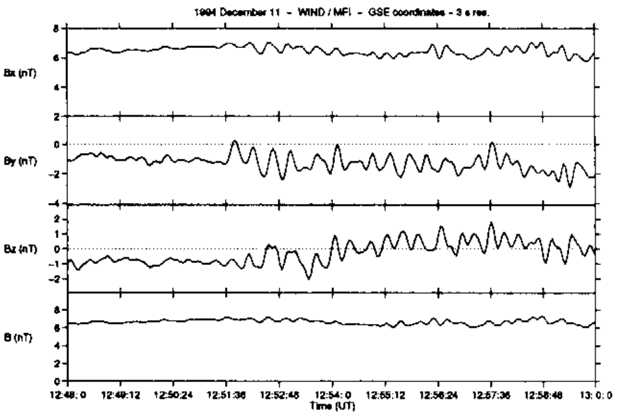

Fig. 2: Magnetic field components (in GSE system) and magnitude between 1250 UT and 1300 UT on 12/11 1994. Prominent large amplitude waves are observed after 12:51:36 UT, the very time when the ion distributions on Figure 1 change from beam-like to ring-like shape. Then the wave amplitude remains very steady (about 2 nT peak-to-peak).

Other examples of such gyrating ion distributions have already been reported by Meziane et al. (1997) and by Meziane et al. (2000) at distances between 17 R_E and 83 R_E from the shock. The bulk velocity of all these distributions is not consistent with the velocity computed for a specular reflection at the shock surface of a portion of incident solar wind ions.

2.2 Low frequency waves

Figure 2 displays the dc magnetic field components (Lepping et al., 1995) in the GSE coordinates around the times when the ion distributions in Figure 1 were observed. Large amplitude low frequency oscillations are displayed mainly on the B_Y and B_Z components with a peak-to-peak amplitude of 2 nT, typically. The observed period in the spacecraft frame, computed from the mean interval between wave crests, is 22 ± 4 s while the local proton gyroperiod is about 10 s.

We have studied the magnetic fluctuations by using the classical minimum variance technique. This characterizes the waves, giving the direction of propagation with respect to the background magnetic field $\mathbf{B}_0$, the polarization and the relative wave amplitude $\delta B/B_0$. The usual convention is used to order the eigenvalues of the covariance matrix of the field perturbations $\lambda_1>\lambda_2>\lambda_3$ (maximum, intermediate and minimum variances, respectively). The direction of minimum variance gives the direction of propagation with respect to the background magnetic field $\mathbf{B_0}$, computed as the averaged field vector during the time interval analyzed, and provides the angle θ_{kB} between the wave vector **k** and $\pm\mathbf{B_0}$. If one assumes that λ_3 represents the isotropic background noise perturbation, the error on this determination can be estimated by $\Delta\theta_{kB}=\tan^{-1}(\lambda_3/\lambda_2-\lambda_3)$. The polarization of the field perturbation can be determined with respect to the ambient field $\mathbf{B_0}$ in the spacecraft frame. The waves can be reasonably taken as plane waves ($\lambda_2/\lambda_3\approx23$) with the direction of propagation nearly parallel to $\mathbf{B_0}$ ($\theta_{kB}=8\pm3°$). The waves are nearly circularly polarized ($\lambda_1/\lambda_2\approx1.9$) and left-handed in the spacecraft frame; the relative wave amplitude is $\delta B/B_0\approx0.2$.

3 Possibility of cyclotron resonance

In agreement with earlier investigations (Thomsen et al., 1985; Fuselier et al., 1994), the gyrating ion distributions discussed here are always associated with such highly transverse weakly compressive low frequency waves propagating at small angles relative to the IMF. The angle θ_{kV} between the wave vector and the solar wind velocity has been computed by using the proton velocity averaged over each time interval studied. It can be noticed that this angle is always between ~150° and 160°, consistent with a propagation toward the sun. To investigate as quantitatively as possible the possibility of local resonance between the observed waves and gyrating ion populations, we compare the observed wave periods T_{obs} with the periods T_{pred} one would predict in the spacecraft frame for waves in cyclotron resonance with the locally observed distributions.

Consideration on the branches of the dispersion relation in the Brillouin plane helps to determine what kind of wave mode is a good candidate for cyclotron resonance (e.g. Brinca, 1991). The wave mode is necessarily a right-hand mode co-streaming with the ions along the ambient magnetic field, i.e., towards the sun, so that it can resonate with a backstreaming ion population ($\mathbf{k}.\mathbf{V}_{//}$ must be positive). The cyclotron resonance condition is:

$$\omega-k_{//}V_{//}+\Omega_p=0 \qquad (1)$$

where ω is the wave frequency in the solar wind rest frame, Ω_p is the proton gyrofrequency, $k_{//}$ is the component of the wave vector parallel to the background magnetic field, and $V_{//}$ is the parallel component of the resonant ion velocity (relative to the solar wind). By assuming $\omega<<\Omega_p$, we can make the approximation:

$$k_{//}\approx\Omega_p/V_{//} \qquad (2)$$

The parallel wavelengths $\lambda_{//}$ of these resonant waves all are of the order of 1 R_E. In the spacecraft frame, these waves would have a Doppler-shifted frequency of

$$\omega'=\omega+\mathbf{k}\bullet\mathbf{V}_{sw}\approx k_{//}V_{sw}\cos\theta_{kV}/\cos\theta_{kB} \qquad (3)$$

Then using the experimental values, we have computed the predicted wave periods $T_{pred}\equiv2\pi/\omega'$ according to (2) and (3) and compared it with the observed period T_{obs}. For instance, for Dec.11, 1994 at 12:54:10 UT (event (b) of Meziane et al. (1997)), $V_{//}=800\pm30$ km/s, which gives $T_{pred}=20\pm2\,s$ while $T_{obs}=22\pm4\,s$. The observed periods are systematically close to those predicted, taking into account the experimental uncertainties (Meziane et al., 1997; 2000). This strongly supports the possibility that local cyclotron resonance occurs for these events.

4 Linear theory

However, a more careful analysis of all these events reveals that the observed parallel velocities generally appear a little bit too small for T_{pred} to match T_{obs}. For the majority of these events, field-aligned beams are clearly observed just before the ring-like distributions and their characteristics can be derived. We then make the same test of period matching for the field-aligned beams. To illustrate that, in Figure 1, at 12:49:54 UT, $V_{//}=1050\pm50$ km/s which gives T_{pred} = 23 s while $T_{obs}=22\pm4\,s$. Thus, this beam distribution could have generated the observed wave from an ion/ion beam instability (e.g., Gary, 1991).

To test this hypothesis, we solve the linear dispersion relation for parallel electromagnetic modes by using the WHAMP program (Rönmark et al., 1982). We use a plasma model with parameters as close as possible to the WIND 3DP observations: $N_p=6$ cm^{-3}, $N_{beam}/N_p=6.10^{-3}$, $T_e=T_p=7$ eV, $T_{beam}/T_p=54$, $V_{Alfven}/c=2.10^{-4}$. The results are shown on Figure 3 for the unstable ion/ion right-hand mode. The real frequency at the growth rate maximum is $\omega_{max}/\Omega_p=0.098$ and $\gamma_{max}/\Omega_p=0.110$. The phase velocity is $V_\phi=1.8\ V_A$ (109 km/s), in good agreement with the value in the plasma frame computed from the observations (105 km/s). The

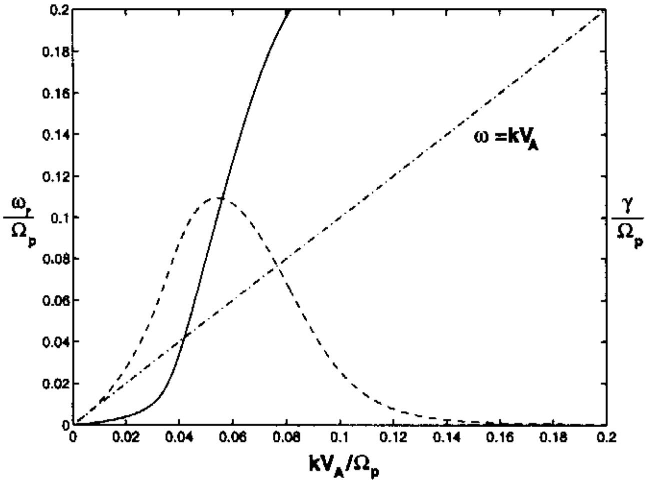

Fig. 3 Real frequency (solid line) and growth rate (dashed line) of the ion/ion right-hand resonant instability as functions of wavenumber at propagation parallel to $\mathbf{B}_0$ for experimental parameters suitable for the beam distribution displayed on the upper left panel of Figure 1.

associated wavelength is λ_{max} =10,900 km, in very good agreement with the experimental value λ_{exp} = 10,500 ± 500 km ~ 1.6 R_E.

5 Nonlinear wave-particle trapping

Among the gyrating ion distributions reported, no event is consistent with a specular reflection at the Earth's bow shock (see discussion in Meziane et al., 2000). They are observed by far at too large distance (D_{shock}>20 R_E) while cut-off distance for shock-issued gyrating ion distributions is $\leq$ 4 R_E (Thomsen et al., 1985; Fuselier et al., 1994). It is thus necessary to invoke a local production mechanism for these upstream distributions. The predicted wave periods in the s/c frame for cyclotron resonance with right-hand mode waves are close to the observed periods. This a clear indication of wave particle-interaction. Field-aligned beams observed just before the ring-like distributions (see Figure 1) appear even in closer cyclotron resonance with the ULF waves observed later. Results of the linear theory show that the field-aligned beams are very good candidates to generate the waves. Thus, it is quite natural to check the validity of a possible scenario implying wave generation from the ion beam instability and nonlinear beam disruption by the excited wave to produce the observed ring-like distributions.

For this, we make some theoretical considerations about the nonlinear trapping of ions by an electromagnetic monochromatic 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 $V\phi$ (<<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., Roux and Solomon, 1970; Gendrin 1974; Matsumoto, 1985; Le Quéau and Roux, 1987):

$$T = w_{//}^2 + w_{\perp}^2 = C_1 \tag{4}$$

and

$$S = (w_{//} - 1)^2 - 2\frac{\Omega_1}{\Omega_0} w_{\perp} \sin\psi = C_2 \tag{5}$$

where

$$\mathbf{w} = \frac{k_{//}}{\Omega_0}\mathbf{v} \tag{5.1}$$

$$\Omega_{0,1} = \frac{qB_{0,1}}{m} \tag{5.2}$$

$$\psi = \varphi + k_{//} z \tag{5.3}$$

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). Using the pitch-angle α such as

$$\tan\alpha = \frac{w_{\perp}}{w_{//}} \tag{6}$$

the equations of motions

$$\frac{d\alpha}{dt} = -\delta\cos\psi \tag{7}$$

and

$$\frac{d\psi}{dt} = \delta\cot\alpha\sin\psi + \sqrt{T}\cos\alpha - 1 \tag{8}$$

where

$$\delta = \frac{\Omega_1}{\Omega_0} = \frac{\delta B_{\perp}}{B_0} \tag{9}$$

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 Eqs (4) and (5.1) that we have T=1. Then, by linearizing the trapping potential, around $\psi_0 = \pi/2$, it is straightforward to show

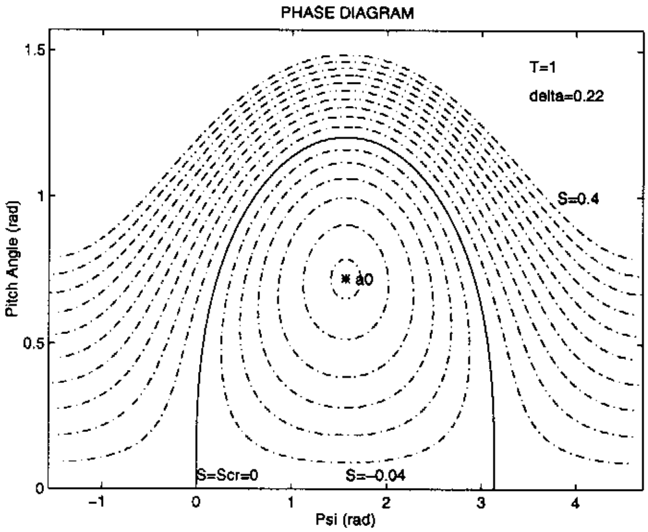

Fig. 4. Possible trajectories in the phase space (α, ψ) for both fixed T (i.e., energy) and δ (i.e., wave amplitude). The contour plot S=Scr is the separatrix between untrapped and trapped particles. The center of the trapping cell (a_0) is defined by the angle α_0 for which the invariant S is singular.

that this singularity corresponds to $\alpha_0 \approx (2\delta)^{1/3}$, defining the center of the trapping cells. The theoretical phase diagram is shown on Figure 4. The trapping frequency around α_0 is:

$$\Omega_T \propto \Omega_0^{1/3} \Omega_1^{2/3} \tag{10}$$

Then theoretical particle distribution in the $(V_{//}, V_{\perp})$ plane can be derived, displaying the pitch-angle width for a constant value of $S(\alpha, \psi)$ as is shown on Figure 5. 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 (a_0) associated with the pitch angle α_0.

To illustrate this, we use the example of experimental results described in section 2. For 12:51:37 UT (see Figure 1), the peak of the gyrating ion distribution function corresponds to a pitch-angle α_{obs}=40±5° (with $V_\phi = 1.8 V_A$) while the theoretical value using $\delta = 0.22$ from the observations is α_0=41°. Similar results are obtained for the other reported events. This good agreement 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.

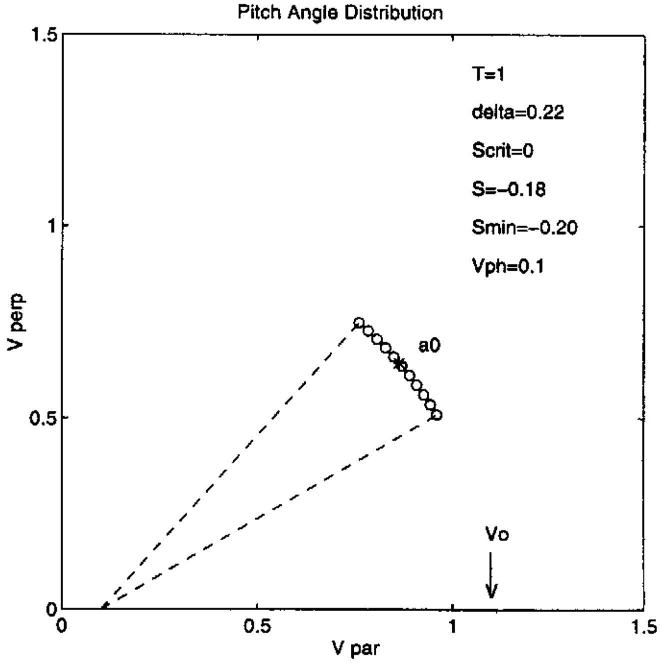

Fig. 5. Theoretical particle distribution in the $(V_{//}, V_{\perp})$ plane displaying the pitch-angle width for a constant value of the second invariant of the movement $S(\alpha, \psi)$. V_0 is the initial velocity of the cyclotron resonant beam (T=1).

6 Conclusion

We have investigated a local production mechanism to explain the existence of the well-defined gyrating ring-like ion distributions reported from the WIND-3DP measurements at much larger distances from the Earth's bow shock than previous observations. We have analyzed the associated large amplitude low frequency waves and show that they are consistent with right-hand mode waves in the plasma frame (anomalous Doppler shift) which can be in cyclotron resonance with the ions. We 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 lead to a very good agreement with the observed wave mode. Then the possibility of producing the ring-like distributions from the disruption of the beam by the excited wave has led to a good quantitative agreement from nonlinear trapping theory.

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