Plasma Transport and Heating Due to Kinetic Alfvén Waves

Investigators: J. R. Johnson, C. Z. Cheng

That these transverse waves are nearly always seen at the magnetopause and have large amplitude, with magnetic fluctuations often as large as the ambient field suggest that they may be responsible for transport and heating at the magnetopause. Observations in the magnetosheath and magnetopause indicate that plasma that leaks across the boundary often have distinctive particle distributions indicative of acceleration processes. For example, electron distributions in the boundary layer are often found to be accelerated in the direction parallel to the magnetic field, while ions in the sheath transition layer and boundary layers often exhibit significant temperature anisotropy with the perpendicular temperature greater than the parallel temperature.

An unusual low energy component of the ion distribution significantly heated in the perpendicular direction was recently observed by WIND/3DP in the low-latitude boundary layer and magnetosheath as shown in Figure 1. Similar ion distributions were also detected by the POLAR satellite in the magnetosheath near the high-latitude dayside magnetopause. These unusual ion features seem to be observed in the absence of the electron signatures typically associated with reconnection suggesting that they may result from wave-particle interaction.

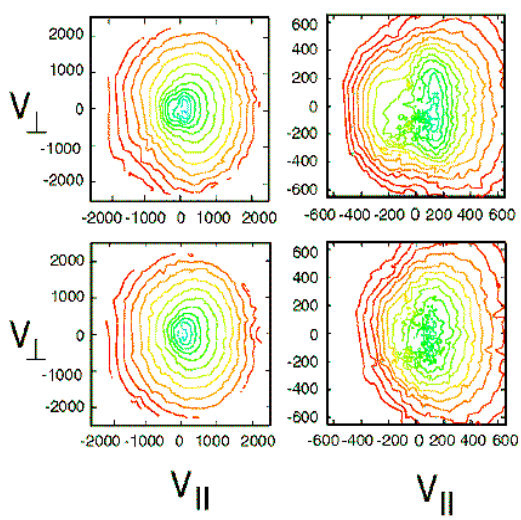

Figure 1 Ion distribution near the magnetopause measured by the WIND/3DP instrument (9/16/1995 at 14:14 universal time) [Courtesy M. Wilber, G. Park and R. Lin]. Contours represent constant value of the distribution function at logarithmic increments. The distribution is a function of perpendicular and parallel velocity measured in km/s. The upper left panel is the measured distribution for all ions detected by the plasma instrument at 14:14 universal time. The upper right panel shows the low energy part of the distribution at that same time. Notice that the low energy core of the distribution is heated predominately in the perpendicular direction. The low energy distribution is flatter than the more energetic part of the distribution. The lower panels show the distribution function at a later time. The same features can also be seen at that time.

In both observations, particles appeared to have undergone adiabatic streaming from a stronger magnetic field region with heating occurring near the magnetopause as deduced from the mirror ratios. The low energy ions appear to have been heated perpendicular to the magnetic field and in some events the core of the distribution appears to be flattened as seen in Figure II-1. Indeed, a flattening of the low energy component of the ion

distribution in the inner boundary layer as compared with the magnetosheath is typically observed during magnetoapause crossings, suggests that there is a source of heating is close to the magnetopause boundary.

Recently, we showed that magnetic field fluctuations at the magnetopause are likely the result of a mode conversion process which focuses wave energy at the magnetopause into large amplitude kinetic Alfven waves.

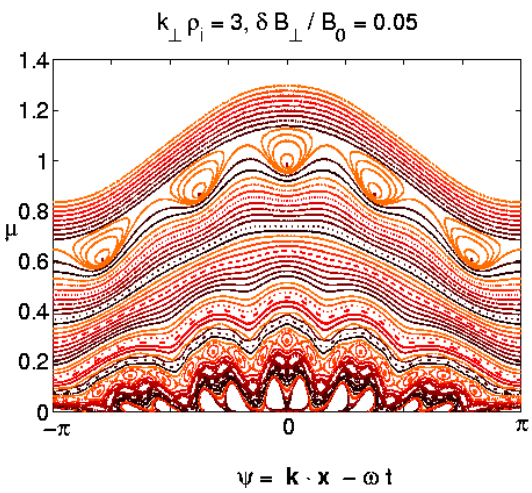

Figure 2 Phase space plot of magnetic moment,μ, vs wave phase, $\psi = k \bullet x - \omega t$ in the presence of a kinetic Alfven wave. The amplitude is just below the threshold condition for stochastic behavior.

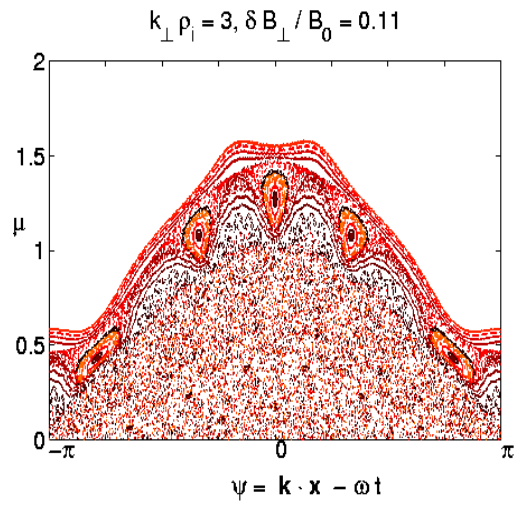

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Figure 3 Phase space plot when the amplitude is well above the threshold condition. For these conditions, a Maxwellian distribution develops core flattening in about 20 ion cyclotron periods.

consistent with parallel electron heating, but they also can produce observed ion heating. To understand the process, we considered particle motion in a large amplitude kinetic Alfven wave with wavelength characteristic of the mode conversion process. Our study consisted of a sequence of Poincare sections taken at different wave amplitudes which demonstrate the onset of stochasticity. For sufficiently large wave amplitude, the particle orbits become stochastic as shown in Figures II-2 and II-3.

Figure 2 shows the Poincare section for $\delta B/B=0.05$ with $\omega/\Omega_{ci}=0.2$, where ω is the wave frequency and Ω_{ci} is the ion gyrofrequency. The magnetic moment, μ (normalized to the magnetic moment obtained using the initial ion thermal velocity) is plotted versus the wave phase, $\psi=k\bullet x-\omega t$.

The period five island chain associated with a nonlinear wave/gyroperiod resonance is readily visible. Above that chain, the high-energy particles do not show any structure related to gyromotion and simply float up and down in the wave. Other islands chains have also appeared at lower energies. The obvious island periods are in the sequence: 26,

21, 58, 16, 27 and so forth. Islands in the period 16 and 21 chains have just begun to overlap.

A slight increase in wave amplitude allows the phase space islands to merge and regions of stochastic orbits to appear. Low energy particles can wander to higher energies leading to heating of the core of the distribution. For larger wave amplitude, $\delta B/B=0.11$, the entire phase space, below a bounding energy, becomes globally stochastic as shown in Figure 3. The heating that occurs is anisotropic with perpendicular temperature greater than parallel temperature. Because low frequency waves at the magnetopause often are observed with $\delta B/B=0.1$ or larger, there would be sufficient nonlinearity to produce ion heating and stochastic particle behavior.

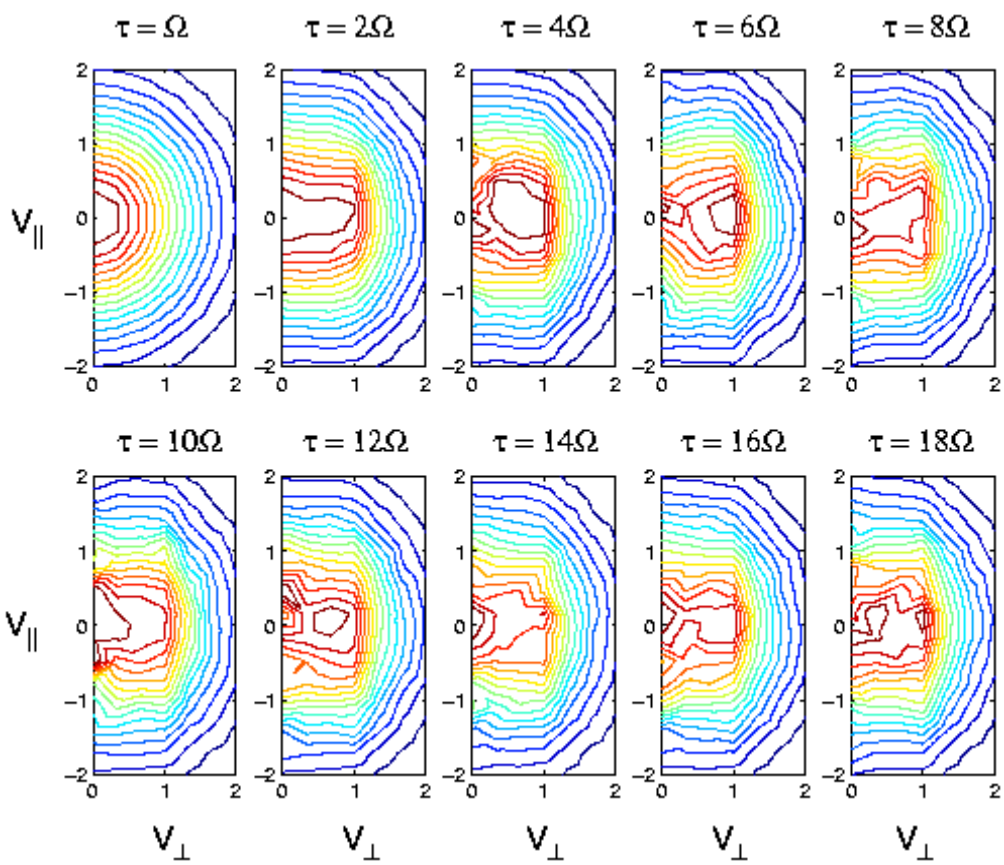

Figure 4. Ion distribution in the presence of a kinetic Alfven wave. The Alfven wave has $\delta B/B=0.2$ and $k_{\perp}\rho=3$, where ρ is the ion gyroradius. The distribution begins as a Maxwellian with v normalized to the thermal velocity at t=0. In the presence of the wave, the distribution quickly develops a heated population within 10 ion gyroperiods. The distribution can be compared with the measured distributions observed by WIND which are shown in Figure II-1.

In Figure 4 we show the evolution of the ion distribution which begins as a Maxwellian. As time proceeds, the particles the low energy particles are heated leading to a flattening

of the distribution and increase in perpendicular temperature. The heated distribution can be compared with the low energy distribution presented in Figure II-4. Note that the perpendicular and parallel axes are switched in the two figures.

Our results demonstrated: (1) stochastic ion heating can result through nonlinear coupling between low frequency waves and cyclotron motion, (2) ions can be heated transverse to the magnetic field leading to temperature anisotropy, with perpendicular temperature greater than parallel temperature, as observed at the magnetopause, and (3) the stochastic process flattens the core of the distribution function as is observed near the magnetopause.