Thermalization of Neutral-Beam-Injected Ions by Lower Hybrid Waves in Jupiter's Magnetosphere

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A theoretical analysis of lower hybrid wave generation by a ring distribution of superthermal ions is presented. A kinetic instability of waves traveling across the magnetic field occurs when fast neutrals escaping from the Io plasma torus are reionized and accelerated to corotation speed in Jupiter's magnetosphere. Instability is possible for modest threshold vaules of $V/a_0=3-7$ where V is the pickup gyrospeed and a_0 is the background-ion thermal speed. Consequent effects include the relaxation of the pickup-ion distribution and the acceleration of superthermal electrons.

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The ionization of energetic neutral-atom beams in plasma is a practical means of auxiliary heating for fusion reactors under development.[1] The unencumbered simplicity of the scheme makes it likely that similar processes would be found in natural settings.[2–4] Indeed, the close parallelism of physical processes thought to occur in the Io plasma torus[5,6] with those in fusion plasmas is rather remarkable. In this paper we shall advance a common theoretical mechanism as an explanation for the presence of medium-energy particles and anomalous plasma-wave activity measured by the Voyager spacecraft at Jupiter.

The problem concerns the observation of a type of broadband electrostatic noise in the outer parts of the Jovian magnetosphere with systematic morphological features.[7] The noise showed a propensity to be more intense in spatial regions where the plasma was cool (~ 10 eV), thus exhibiting a sensitivity to ambient plasma temperature.[8] The plasma probe on the spacecraft[9] measured *in situ* a heterogeneous mixture of warm protons, sulfur, and oxygen ions (100 eV to 1 keV) composing a "halo" embedded in which was a stratum of cool, dense Iogenic heavy-ion plasma located at the centrifugal equator. Assessing all known plasma sources we concluded that the broadband noise, which included a prominent component near the lower hybrid (LH) frequency, was either a dissipation effect associated with radial transport outwards of the cool Iogenic plasma or a manifestation of energy exchange between superthermal ionospheric protons and Iogenic plasma.[8]

A subsequent theoretical study uncovered another important mode of material transport that featured prominently in the mass and energy budget of the Jovian magnetosphere. It was found that charge exchange between corotating Io torus ions and the neutral-atom clouds that disperse off of Io produces an intense beam of fast neutral atoms that freely escape the magnetosphere in the form of an annular disc.[10] The reionization of these atoms forming this so-called magnetospheric neutral wind would recycle a fraction of Iogenic matter back into the magnetosphere. Consequentially, this would provide a significant heat source for the magnetosphere since the ionization "pickup" process at large radial distances extracts energy from the planetary rotation as the ions are swept up to corotation with comparable drift energy and gyroenergy.

In this paper we analyze an instability of the Jovian neutral-beam-injected (NBI) ion population that is analogous to that considered for fusion devices.[11–13] The thermalization of these NBI ions by the lower hybrid mode[14] will afford a ready explanation for the presence of heavy ions in the warm particle halo as well as the broadband electrostatic noise referred to earlier.

Neutral atoms in the wind initially have a speed corresponding to the corotation velocity at Io's orbit of 75 km/s which is much greater than the escape velocity of ~ 25 km/s. Jovian gravity will reduce this by a small amount to an asymptotic value of ~ 70 km/s. The primary mechanisms for reionization are (1) charge exchange with ambient corotating ions, (2) electron impact with hot (~ 1 keV) magnetospheric electrons, and (3) photoionization from solar ultraviolet radiation.[10] The above are ordered in increasing importance with radial distance from the planet.

Representative values for the ion injection rate may be derived as a lower bound by the assumption that only photoionization is operative. Reference 10 gives estimates for neutral-atom densities in the wind and photoionization frequencies for oxygen and sulfur which when evaluated at a radial distance of $20R_J$ yield $\dot{n}_{O^+}=1\times10^{-8}$ cm^{-3} s^{-1} and $\dot{n}_{S^+}=6\times10^{-8}$ cm^{-3} s^{-1}. A suggested value for the residence time of 10^6 s (Barbosa[15]) then specifies a density of pickup ions $n_1=0.01$–0.06 cm^{-3} depending on whether the oxygen or sulfur rate is more appropriate. At this radial distance the plasma probe obtained a density of $n_e \simeq 1$ cm^{-3} for the cool thermal plasma[9] so that the relative ion concentration may be estimated as $n_1/n_e=0.01$ -0.06.

The pickup of these ions at large distances where the local corotation speed $V=V_{CR} >> 75$ km/s will produce a distribution function with a sharp peak in the velocity component perpendicular to the magnetic field with only a small velocity spread about the pickup velocity. This effect is appropriately modeled in the corotating frame of reference by a ring distribution function,[16]

$$f(v_\perp)=\frac{n_1}{\pi\Gamma(N+1)a_\perp^2}\left(\frac{v_\perp}{a_\perp}\right)^{2N}\exp\left(-\frac{v_\perp^2}{a_\perp^2}\right). \quad (1)$$

Here, N is a parameter that measures the sharpness of the peak occurring at $V=a_\perp\sqrt{N}$ and n_1 is the density of the pickup ions in a background of cooler thermal ions with density $n_0 >> n_1$.

This type of ion distribution is unstable to a variety of modes.[12] We concentrate on the specific case of lower hybrid waves with frequency $\omega_{\rm LH}=(\Omega_{ce}\Omega_{ci})^{1/2}$ for high-density, $\omega_{pe}^2 >> \omega_{ce}^2$, conditions. If the rectilinear ion orbit approximation[17] is employed, it may be shown that the growth rate γ for LH wave propagating perpendicularly to the magnetic field is given by[6]

$$\gamma=\gamma_0+\gamma_1, \quad (2)$$

where

$$\gamma_0/\omega \simeq -\sqrt{\pi}B^3\exp(-B^2) \quad (3)$$

represents damping on the background ions and

$$\frac{\gamma_1}{\omega}\simeq-\frac{n_1}{n_e}\frac{2}{\Gamma(N+1)}b^3\exp(-b^2)\int_0^\infty dt\exp(-t^2)(b^2+t^2)^N\left(1-\frac{N}{b^2+t^2}\right) \quad (4)$$

represents the contribution from the pickup ions. In the above, which is valid for $|\gamma/\omega| << 1$, the quantity $b=\omega/ka_\perp$, while $B=\omega/ka_0$ with a_0 being the background-ion thermal speed. Electron Landau damping is negligible for near-perpendicular propagation but becomes important at oblique angles of the wave vector.[6]

Figure 1 shows a plot of the growth rate versus b for several values of N. The solid lines correspond to growth with background-ion damping neglected, $\gamma_0=0$. The dotted curves illustrate the effect of how damping on the background ion inhibits the excitation of modes with small phase velocity. It is evident that for this particular choice of $V/a_0=5$ and $n_1/n_e=0.1$ the instability is completely suppressed when the ring anisotropy $N \lesssim 1$.

The influence of the background ions is examined further in Fig. 2 where instability thresholds are plotted. The maximum of the expression in (2) was computed for fixed values of N and n_1/n_e, and the ratio V/a_0 was increased until marginal stability ($\gamma=0$) was reached. For V/a_0 greater than the threshold value positive growth ($\gamma>0$) is obtained. It is seen that for a given N the onset of instability occurs for a narrow range of V/a_0 values with only a weak dependence on the relative concentration of pickup ions n_1/n_e.

In conclusion, lower hybrid waves propagating perpendicularly to the magnetic field can be driven unstable by a low-density superthermal ring distribution of neutral-beam-injected ions. The primary condition for instability is that the ratio of the pickup-ion gyrospeed to the background-ion thermal speed be larger than a threshold value depending on the ring anisotropy index N. For moderate values of N considered here, a range of $V/a_0 \gtrsim 3$–7 is sufficient for instability and this condition is easly met by NBI pickup ions in the Jovian magnetosphere. Also, the relative concentration of pickup ions does not strongly affect the threshold criterion when $n_1/n_e=0.01$–0.1 as appropriate to the middle magnetosphere, the major role of the background ions being to provide a suitably cool medium in which to propagate the waves.

Because of the low plasma density, the pickup ions are collisionless over their residence time in the middle-outer magnetosphere. An ion with energy $E_i=100$ eV slowing down in a plasma with $n_e=1$ $\rm cm^{-3}$ and $T_e=10$ eV has collision times of $\tau_{ii}\sim 2\times10^9$ s and $\tau_{ie}\sim10^{10}$ s which are large compared with a residence time of $\tau_c=10^6$ s. In the absence of collisions, the LH waves then serve as a means of relaxing the pickup-ion distribution in the manner described by, e.g., Ref. 14. A calculation of the quasilinear time scale for this process based on a measured wave electric field strength of $E_{\rm rms}\simeq 1$ mV/m and $f_{\rm LH}\simeq 32$ Hz indicates that $\tau_{\rm QL}\lesssim\tau_c$ for ion energies $E_i \lesssim 1$ keV. Thus, the scattering of pickup ions by LH waves is most likely the dominant effect

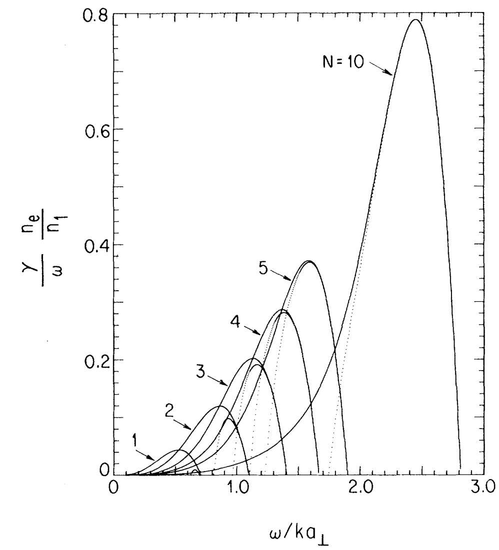

FIG. 1. Growth rates for the ring distribution of ions with (without) background-ion Landau damping included are indicated by dotted (solid) lines, respectively.

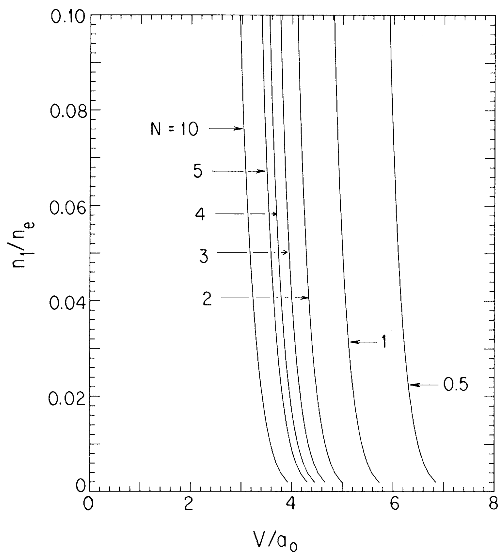

FIG. 2. Marginal stability thresholds are calculated for several values of the ring anisotropy index N.

occurring in the tenuous plasma of the distant magnetosphere. In contrast, the high-density Io plasma torus, the major source of heavy-ion plasma in the magnetosphere, is collision dominated and LH wave-particle interactions have only a secondary role.[5,6] The transition between these two regimes occurs roughly at a radial distance of $10R_J$ where the electron density has dropped to $n_e \leqslant 100\ \text{cm}^{-3}$.

It is interesting to note that a recent investigation of perpendicular NBI heating in tokamak plasma suggests that the ions slow down classically.[18] Thus, the ion behavior is closer to that found in the Io torus proper (which is fueled by another NBI process). However, pending actual wave measurements at lower hybrid frequencies in these and other devices, the possibility of collective effects being significant still exists, and the LH interaction described here may have analogs in the lower-density perpendicular NBI experiments.

This process also affords a possible mechanism for heat exchange between the pickup ions and cool background thermal plasma resulting in the local acceleration of superthermal ions and especially electrons by lower hybrid waves in the middle magnetosphere. Previously, the origin of the magnetospheric hot electrons was uncertain, but the possibility of a local acceleration was allued to.[9] The effect on the pickup ions is to produce a diffusion in the perpendicular velocity component rather than a systematic slowing as from Coulomb dynamical friction with electrons. However, in the sense that the distribution function is filled in at low velocities and that an energy transfer to the background ions and electrons occurs tending towards energy equipartition, the process may be regarded as a thermalization of the pickup ions.

The theory represented here thus gives a satisfactory explanation for the plasma-wave observations of broadband electrostatic noise which favored spatial regions of cool plasma. The sensitivity of the instability to Landau damping on the background ions establishes a theoretical basis for this empirically derived result.[8] Although the mechanism provides an ostensible reason for the noise, it is possible that other contributing sources are present also. An alternative process of current-driven LH waves related to the transport of Iogenic plasma outwards may predominate. Such a mechanism which exhibits the specified dependence on ion temperature is presently under investigation. A full elaboration of the results and conclusions will be given elsewhere.

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