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The Landau damping of magnetospherically reflected whistlers within the plasmasphere

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[1] Evidence for significant energetic electron precipitation by magnetospherically reflected (MR) whistlers has recently been found in SAMPEX energetic electron data [*Blake et al.*, 2001], implying that these waves undergo many reflections before being attenuated through Landau damping. We quantify the Landau damping of MR whistlers, using recent energetic electron data from the HYDRA instrument on POLAR and show that the MR wave components can endure for as long as ~20 seconds and undergo as many as 17 reflections before experiencing a 6 dB power loss due to Landau damping. Our results suggest that MR whistler wave energy may thus significantly enhance the total amount of energetic electron precipitation induced by each individual lightning discharge. *INDEX TERMS:* 0689 Electromagnetics: Wave propagation (4275); 2772 Magnetospheric Physics: Plasma waves and instabilities; 2716 Magnetospheric Physics: Energetic particles, precipitating; 2720 Magnetospheric Physics: Energetic particles, trapped

1. Introduction

[2] This paper concerns the Landau damping of magnetospherically reflected (MR) lightning-generated whistlers, which potentially can strongly affect the pitch angles of energetic electrons in the radiation belts, leading to significant particle precipitation [*Jasna et al.*, 1990, 1992; *Ristić-Djurović et al.*, 1998]. The importance of this effect is underscored by the fact that up to 2000 thunderstorms are active over the Earth's surface at any given time, providing a global lightning discharge rate of ~30 to 100 per second [*Volland*, 1984]. On average these discharges radiate intense electromagnetic pulses of roughly 20 GW peak power, and a significant fraction of this power lies in the ELF/VLF frequency range. A large portion of this wave energy propagates up into the magnetosphere as a nonducted whistler.

[3] Wave components with frequency less than 10 kHz generally become MR whistlers [*Edgar*, 1976], and sometimes undergo as many as 20 reflections between conjugate hemispheres, often forming bands of wave energy resembling hiss [*Sonwalkar and Inan*, 1989; *Draganov et al.*, 1992, 1993]. Recent work indicates that MR whistlers can resonantly interact with energetic electrons over a wide range of L-shells [*Jasna et al.*, 1990; *Ristić-Djurović et al.*, 1998] and that pitch angle scattering coefficents for these waves can be at least as large as those for ducted waves [*Inan and Bell*, 1991]. This scattering is in addition to the scattering that initially takes place as the whistler first propagates across the magnetic equator into the conjugate hemisphere [*Lauben et al.*,1999], and may produce significantly more precipitation as the MR whistler reflects back and forth across the magnetic equator, scattering electrons in pitch angle during each traverse along the field lines.

[4] *Thorne and Horne* [1994] have suggested that MR whistlers would be strongly absorbed through Landau damping. If this were true, MR whistlers would not be an important agent for producing energetic electron precipitation. On the other hand, observations from numerous spacecraft indicate that MR whistler groups with multiple elements, such as that shown in Figure 1, are common throughout the plasmasphere [*Edgar*, 1976]. Furthermore, recent data from the SAMPEX spacecraft suggest that MR whistlers undergoing many reflections in the plasmasphere may be responsible for energetic electron precipitation fluxes commonly detected in the drift loss cone [*Blake et al.*, 2001].

[5] In view of the potential importance of MR whistlers, the apparent disparity between theory and observation needs to be reconciled. In the present paper we make use of a large data set from the HYDRA energetic electron experiment [*Scudder et al.*, 1995] on the POLAR spacecraft in order to calculate the expected Landau damping rates of MR whistlers (Preliminary results were presented at the Dec. 1999 AGU meeting [*Bell et al.*, 1999]). Our results indicate that the OGO 3 fluxes used by *Thorne and Horne* in their Landau damping model are not typical of those observed within the plasmasphere by HYDRA, and that the expected Landau damping of MR whistlers is indeed small enough that the MR wave components can endure as long as ~20 seconds and undergo as many as 17 reflections within the plasmasphere before experiencing a 6 dB power loss.

2. Observations

[6] Figure 1 shows a typical frequency-time spectrogram of a group of MR whistlers observed on the POLAR spacecraft with the University of Iowa Plasma Wave Instrument [*Gurnett et al.*, 1995]. At the time, POLAR was located at L = 2.6, near the geomagnetic equatorial plane. A single lightning discharge has given rise to a group of 8 MR whistlers, produced as the VLF waves radiated by the lightning discharge reflect back and forth between reflection points in the conjugate hemispheres [*Edgar*, 1976]. The first whistler in the set of 8 arrives at the spacecraft after propagating directly from the ground to the spacecraft. The remaining MR whistlers have crossed the magnetic equator and reflected n-1 times, where n is the number shown in the Figure. MR whistlers are generally observed within the plasmasphere over the region $1.5 \leq L \leq 4$, and there have

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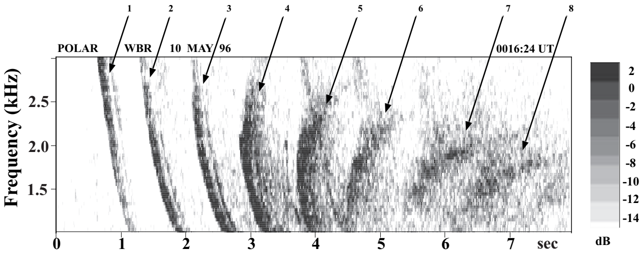

Figure 1. An example of a group of MR whistlers observed on the POLAR spacecraft.

been no published observations of MR whistlers in the region $L > 4$, even during magnetically quiet periods. Thus the energetic electron population of interest with respect to the Landau damping of MR whistlers is that in the region $L \leq 4$.

[7] The HYDRA energetic electron and ion instrument on the POLAR spacecraft has been described by *Scudder et al.* [1995]. We concentrate on energetic electron spectra over the energy range 100 eV – 1.5 keV, since these are the particles most heavily involved in the Landau damping of MR whistlers. Figure 2 shows a contour plot of the HYDRA electron velocity space distribution function, $f(v_\perp, v_\|)$, over the 10 eV – 1.5 keV energy range at approximately the same time as the MR whistler observations shown in Figure 1. The horizontal axis shows $v_\|$, the velocity parallel to the Earth's magnetic field B, while the vertical axis shows $v_\perp$, the velocity perpendicular to B. The distributions are assumed to be azimuthally symmetric about B, whose direction is shown by the arrowhead. The magnitude of $f(v_\perp, v_\|)$ is indicated by solid-line contours of $\log_{10}[f(v)]$ on the plot. Each axis shows the velocity range from -25 to $+25 \cdot 10^3$ km/sec. The maximum velocity corresponds to an electron energy of approximately 1.5 keV. It can be seen that $f(v_\perp, v_\|)$ is approximately isotropic for electron energies in the 100 eV – 1.5 keV range. This quasi-isotropic type of distribution is common for electrons of these energies within the plasmasphere.

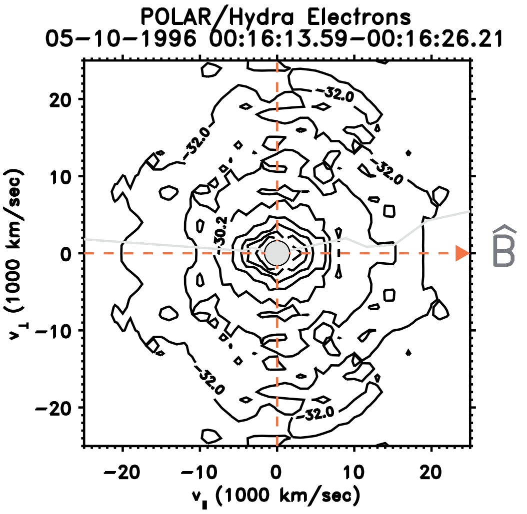

Figure 2. HYDRA energetic electron velocity space distribution function $f(v_\perp, v_\|)$ in units of sec^3/cm^6.

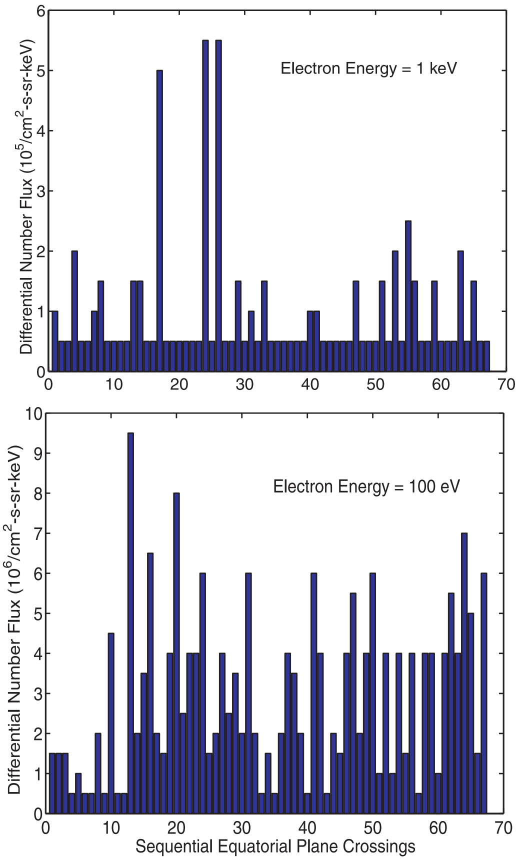

Figure 3. HYDRA plasmaspheric electron differential number flux at the magnetic equator for each POLAR orbit in May, 1996.

[8] For a quasi-isotropic velocity distribution function, $f(v_\perp, v_\|) \simeq f(v)$, and the differential number flux, $dJ(v)/dEd\Omega$, is related to $f(v)$ through the relation $dJ(v)/dEd\Omega = f(v)\, v^2/m$, where $J(v)$ is the number flux, E is the particle energy, Ω is the solid angle, and m is the electron mass [See *Walt*, 1994, equation 5.16, for the momentum space analog of this relationship]. Using the known value of m, we find the relation

$$dJ(v)/dEd\Omega = 1.76 \cdot 10^{18} \cdot f(v)v^2/\Gamma_0, \qquad (1)$$

where $\Gamma_0 = (\mathrm{cm}^2 - \mathrm{s} - \mathrm{sr} - \mathrm{keV})$ and $f(v)$ and v are expressed in cgs units.

[9] Figure 3 summarizes the HYDRA plasmaspheric observations of the parallel differential number flux of 100 eV and 1 keV electrons at the magnetic equator during May, 1996. Overall, these fluxes are rather typical of the HYDRA fluxes observed on the same L shells during most other months since the launch of POLAR. The parallel flux includes all electrons whose velocity vector lies within a 30° cone about B. The upper panel shows the 1 keV electron flux while the lower panel shows the 100 eV electron flux. The L shell range sampled in the data is $L = 2.3 - 4$. The magnetic local time of each observation lies either in the range 2100 – 2300 MLT or 0900 – 1100 MLT. During the observations, the planetary magnetic index lay in the range $0 \leq k_p \leq 4$.

[10] The flux values shown result from rounding off the observed values to the nearest half integer. The exception to this rule concerns all flux values $<0.25 \cdot 10^5/\Gamma_0$ which were

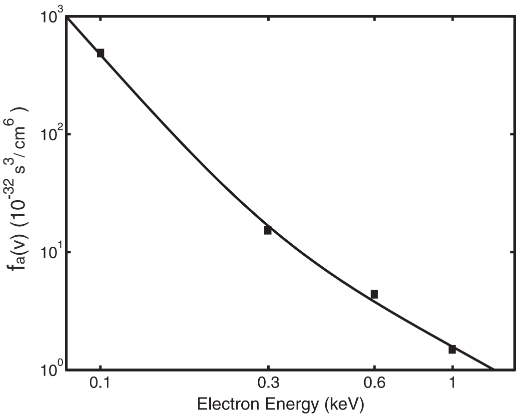

Figure 4. Plot of approximate analytic expression for $f(v)$ as a function of electron energy over the range 100 eV to 1.5 keV.

rounded up to the value $0.5\cdot10^5/\Gamma_0$. Over the month the flux values at 1 keV ranged from $0.5 - 5.5\cdot10^5/\Gamma_0$, and the average flux value was $1.1\cdot10^5/\Gamma_0$. At 100 eV, the flux varied from $0.5 - 9.5\cdot10^6/\Gamma_0$, and the average flux value was $3.2\cdot10^6/\Gamma_0$. In addition, the average flux values at 300 eV and 600 eV (The daily flux values at 300 eV and 600 eV are not shown) were $3.1\cdot10^5/\Gamma_0$ and $1.4\cdot10^5/\Gamma_0$. Of the 67 plasmaspheric equatorial crossings, 39 occured in the region $2.3 \leq L \leq 3.0$ and 28 in the region $3 < L \leq 4$. The average flux level at 1 kev in these two regions differed by less than 30% for the month. The same held true for the average flux level at 100 eV.

[11] Using the average HYDRA fluxes at 100 eV, 300 eV, 600 eV, and 1 keV in conjunction with (1), the following approximate analytic expression for $f(v)$ can be derived:

$$f_a(v) = a/v^4 - b/v^5 + c/v^6 \qquad (2)$$

where $a = 4.9\cdot10^5/(\mathrm{cm}^2 - \mathrm{s})$, $b = 8.3\cdot10^{14}/(\mathrm{cm} - \mathrm{s}^2)$, and $c = 5.4\cdot10^{23}/(s^3)$. Although (2) is derived assuming that $f(v_\perp, v_\|)$ is quasi-isotropic, this is done for simplicity and is not a critical assumption. For example, *Thorne and Horne* [1994] show that Landau damping rates are generally not significantly affected by any anisotropy in $f(v_\perp, v_\|)$.

[12] Figure 4 shows $f_a(v)$ over the energy range 100 eV to 1.5 keV. The black squares at 100 eV, 300 eV, 600 eV and 1 keV are data points derived from (1) using the average flux values quoted above. There is a good fit between the data points and the values for $f_a(v)$ over the energy range shown. In calculating the Landau damping of MR whistlers, as described below, it was found that very little damping was caused by electrons with energy greater than 1 keV and that the waves were damped by 6 dB or more before they experienced damping by electrons of energy less than 100 eV. Thus the use of (2) allows an accurate assessment of the average Landau damping of MR whistlers.

3. Model

[13] We assume that the MR frequency components are injected into the top side ionosphere with vertical wave normals at an altitude of 500 km, and their propagation paths within the plasmasphere are then determined using the Stanford 2-D ray tracing code [*Inan and Bell*, 1991]. The code uses a centered dipole field approximation for B, and a diffusive equilibrium model for the cold plasma. At each step, the code outputs the wave normal angle with respect to B as well as the local densities of the cold plasma constituents and the direction and strength of the Earth's magnetic field. With this information the local spatial Landau damping rate is calculated using (2) in conjunction with the theoretical expression for the Landau damping rate developed by *Brinca* [1972, page 3496, equation (2)] following the work of *Kennel* [1966]. This spatial damping rate is then multiplied by the local step size (typically 1–10 km) and this product is cumulatively summed along the ray path, giving the total damping along the ray path.

[14] Figure 5a shows a typical ray path of an MR whistler component at 3 kHz, injected into the magnetosphere at a latitude of 40^0 S. Figure 5b shows how the amplitude of the wave is attenuated by Landau damping as it moves along its ray path. Landau damping occurs everywhere along the ray path except near the reflection points of the wave. The initial conditions for the ray shown in Figure 5a are approximately the same as the 3 kHz ray shown in Figure 8 of *Thorne and Horne* [1994], and the model of the plasmasphere that we use (with the plasmapause at $L = 4$ with plasma density of $400/cm^3$) is very similar to the model used by *Thorne and Horne* [1994]. Thus we should be able to directly compare the predictions of Figure 5b with the Landau damping calculated for 3 kHz by *Thorne and Horne* [1994] and shown in their Figure 8. Our Figure 5b predicts a Landau damping power loss of 6 dB after a propagation time of approximately 5 seconds. On the other hand, Figure 8 of *Thorne and Horne* [1994] predicts a power loss of approximately 60 dB after a propagation time of approximately 5 seconds. Clearly, the predictions of the two models differ greatly. This circumstance is discussed further below.

[15] The main results of our raytracing study are summarized in Table 1, which shows the length of time, τ, that an MR whistler component can propagate within the magnetosphere before its power is reduced by 6 dB due to Landau damping. There are three panels showing results for 1, 2, 3, 4, and 5 kHz waves injected at the three latitudes: λ = 20°, 30°, and 40°. The total number of magnetic equatorial crossings, n, for each MR component is also shown. As a general rule, MR whistler components of a given frequency endure longer when injected into the magnetosphere from

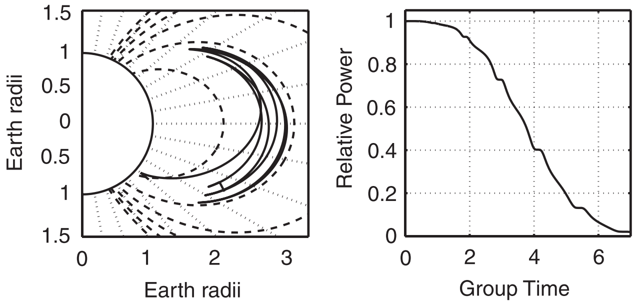

Figure 5. (a) Typical example of the ray path of an MR whistler component at 3 kHz frequency; (b) attenuation of the wave component as it propagates along the ray path.

Table 1. Calculated Time τ that MR Whistler Frequency Components can Propagate Before their Power is Reduced by 6 dB Due to Landau Damping

$\lambda = 20°$			$\lambda = 30°$			$\lambda = 40°$		
f (kHz)	τ (sec)	n	f (kHz)	τ (sec)	n	f (kHz)	τ (sec)	n
1	19.0	17	1	14.7	11	1	11.8	6
2	9.4	14	2	7.7	9	2	6.7	5
3	6.4	12	3	5.5	8	3	4.7	4
4	–	1	4	4.4	7	4	3.8	4
5	–	1	5	3.6	6	5	3.1	4

lower latitudes, as also noted by *Thorne and Horne* [1994]. An exception to this rule occurs for the 4 and 5 kHz waves injected at $\lambda = 20°$. These waves encounter the top side ionosphere in the conjugate hemisphere before they can undergo an MR reflection. The strong vertical plasma density gradients in the top side ionosphere cause the wave normals to rotate towards the vertical, and the wave propagates downward towards the D region, reflects and becomes trapped in the ionosphere. This circumstance is also noted by *Thorne and Horne* [1994]. In all cases the endurance of the wave at fixed injection latitude is a decreasing function of frequency.

4. Discussion

[16] We have calculated the total Landau damping of MR whistlers propagating through the plasmasphere in the presence of energetic electron velocity space distributions such as those typically observed by HYDRA. Our results show that MR whistlers can propagate within the plasmasphere for relatively long time periods (3–19 seconds) before Landau damping reduces the wave power by 6 dB. This result is in keeping with a large body of spacecraft plasma wave data which show that long duration MR whistler trains are very common inside the plasmasphere. The long durations we have found for MR whistler components are also consistent with recent observations from the SAMPEX spacecraft of energetic electrons within the drift loss cone [*Blake et al.*, 2001] which clearly show the L-dependent signature of energetic electron pitch angle scattering by MR whistlers. Since a thunderstorm of moderate intensity can produce a lightning discharge rate of 10/minute, the plasmaspheric region linked to the thunderstorm can be continuously bathed in the electromagnetic fields of the MR whistlers produced by the discharges, leading to enhanced pitch angle scattering of energetic electrons.

[17] As mentioned above, there is a large disparity between the predictions of our model and that of *Thorne and Horne* [1994]. The reason for this disparity appears to be the fact that the OGO 3 differential number flux used by *Thorne and Horne* exceeds the plasmaspheric HYDRA flux (Figure 3) by at least a factor of 10 over the 100 eV – 1.5 keV energy range. This holds true over the entire region $2.3 \leq L \leq 4$. Thus in terms of recent plasmaspheric energetic electron observations, we must conclude that the OGO fluxes used by *Thorne and Horne* are highly atypical. One possible reason for this circumstance lies in the fact that the OGO 3 data used by *Thorne and Horne* was actually acquired in the region $4.2 < L < 5.7$, which is generally not within the plasmasphere, but at the particular time of observation was in fact within the plasmasphere because of very quiet magnetic conditions. There was no particle data acquired by OGO 3 in the region $L < 4$, which is the region where the HYDRA fluxes of Figure 3 have been measured and where MR whistlers are commonly observed. Thus the disparity between our results and those of *Thorne and Horne* [1994] appears to result from their assumption that energetic electron fluxes measured at $4.2 < L < 5.7$ are actually typical of those that exist at $L < 4$. The large HYDRA data set discussed here demonstrates decisively that this is not the case.

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