ON THE NATURE OF HYDROMAGNETIC WHISTLERS

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Fig. 1

Figure 1: Fig. 1

Abstract

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ON THE NATURE OF HYDROMAGNETIC WHISTLERS

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The term "hydromagnetic whistlers" was proposed by Obayashi (^{1}) to denote geomagnetic micropulsations in the range of 1 Hz whose spectrograms consist of series of tones of increasing frequency. Micropulsations of this kind are also known under the name "pearls" (^{2}).

At present the following interpretation of pearls is generally accepted (^{1,3}). Fast charged particles excite packets of waves of left-hand polarization, which then propagate along the lines of force of the geomagnetic field. As the packet propagates upward, its carrier frequency approaches the proton gyrofrequency, and, as a result of dispersion, the packet spreads out: the low-frequency components outrun the high-frequency ones, so that at the Earth' s surface a signal of rising tone is observed. Periodic series of pearls arise as a result of multiple reflections of one and the same packet in magnetically conjugate regions.

Fig. 1

To explain the observed dispersion it is necessary to assume that the carrier frequency is close to one half of the proton gyrofrequency at the top of the signal trajectory (^{4,5}). However, because of the presence in the exosphere of a small admixture of helium ions, the frequency of pearls cannot exceed one quarter of the proton gyrofrequency. Consequently, a modification of the existing theory of pearls is necessary.

1. Let us consider the question quantitatively. The refractive index for waves of left-hand polarization propagating along the external magnetic field in a proton-helium plasma is determined by the expression (^{6})

$$n^2 = -\frac{c^2/v_a^2}{1-\omega/\Omega_1}\left\{1+\frac{N_2/N}{\omega/\Omega_1}\left[\frac{1-\omega/\Omega_1}{1-\omega/\Omega_2}-1\right]\right\}+1,$$

Fig. 2

Figure 2: Fig. 2

where v_a is the Alfvén velocity, N is the electron concentration, $N_{1,2}$ are the ion concentrations, and $\Omega_{1,2}$ are the ion gyrofrequencies. The index 1 refers to protons, and index 2 to helium ions He^+. Figure 1 shows the variation of the square of the refractive index for waves emitted at latitude 63.5° and propagating along a line of force. l/r_e is the distance along the line of force in units of the Earth' s radius, measured from the equatorial plane. The geomagnetic field is assumed to be dipolar; the electron concentration decreases according to the law $N = 1.25 \cdot 10^4 (r/r_e)^{-3}$; the relative con-

The concentration of helium ions is $\xi \equiv N(\mathrm{He}^+)/N(e^-) = 0.01$. The curves in the upper figure correspond to the case in which the wave frequency ω is less than the gyrofrequency of helium ions $\Omega_2^{\min}$ at the apex of the field line: $\omega < \Omega_2^{\min} \simeq 6$ rad/sec. The curves in the lower figure refer to the case in which the wave frequency is greater than the gyrofrequency of helium ions but less than the gyrofrequency of protons: $\Omega_2^{\min} < \omega < \Omega_1^{\min}$. In the second case there are two opaque bands, situated symmetrically with respect to the equatorial plane.

The amplitude transmission coefficient of a wave through these regions of opacity can be estimated by Budden' s formula ([7],[8])

$$D = e^{-\pi\beta}.$$

Here $\beta = (\omega/v_a)(l' - l'')$ is the width of the opaque band in units of Alfvén wavelengths. For $n^2 \gg 1$, $\Omega_2(l') = \omega$ and $\Omega_2(l'') = \omega/(1+3\xi)$.

Figure 2 shows the dependence of the transmission coefficient D on the relative concentration of helium ions ξ for propagation of a wave with frequency $\omega > \Omega_2^{\min}$ along a geomagnetic-field line intersecting the Earth' s surface at latitude 63.5°.

Fig. 2

According to measurements on the OGO-A satellite, helium ions with a relative concentration of order $\xi \sim 10^{-2}$ are present up to altitudes of 30 000 km ([9]). In this case, as is seen from Fig. 2, the transmission coefficient of waves with $\omega > \Omega_2^{\min}$ is practically indistinguishable from zero. Consequently, the frequency of pearls must be less than the gyrofrequency of helium ions at the apex of the signal trajectory. In the classification of Gurnett et al. ([10]), the pearls could be called "helium whistlers."

2. The character of the dispersion in a proton-helium plasma is shown in Fig. 3. In Fig. 3a the normalized group velocity v_{gr}/v_a is plotted along

Fig. 3

Figure 3: Fig. 3

the vertical axis, and the normalized frequency ω/Ω_2 along the horizontal axis. For $\xi \neq 0$, the group velocity

$$v_{\text{gr}} = c\left(\frac{\partial \omega n}{\partial \omega}\right)^{-1}$$

tends to zero when the wave frequency approaches from the left the gyrofrequency of helium ions. Nevertheless, the tones of increasing frequency in pearl spectrograms cannot be explained by wave dispersion alone in the region of helium gyroresonance. Indeed, the relative width of the dispersion region is of order

$$\Delta\omega/\omega \simeq 3\xi \sim 0.03,$$

whereas the relative width of the pearl band is almost an order of magnitude larger. According to preliminary experimental results, at conjugate points the propagation time of pearls from one hemisphere to the other differs somewhat from the propagation time

Fig. 3

···in the reverse direction (11). One of the causes of such asymmetry may be the presence of a stationary plasma flow along the geomagnetic field lines from one hemisphere to the other. When the signal propagates along the flow, its group velocity v_{gr}^{+} is greater than v_{gr}^{-} when propagating in the opposite direction. An analogous situation arises in Fizeau' s experiment on the propagation of light in a moving liquid.

The correction to the group velocity of the signal $\delta v_{\text{gr}} = (v_{\text{gr}}^{+} - v_{\text{gr}}^{-})/2$ is determined by the expression (12)

$$\frac{\delta v_{\text{gr}}}{v_{\text{gr}}} = \frac{\partial \omega \delta n}{\partial \omega} \Big/ \frac{\partial \omega n}{\partial \omega}, \qquad \frac{\delta n}{n} = \left(\frac{u}{c}\right)\frac{\partial \omega n}{\partial \omega},$$

where u is the velocity of the longitudinal drift of the plasma. Fig. 3b shows the dependence of the normalized correction $(\delta v_{\text{gr}}/v_{\text{gr}})/(u/v_a)$ on the normalized wave frequency ω/Ω_2. Since the drift velocity u does not exceed the sound velocity, and hence $(u/v_a) \ll 1$, an appreciable effect is possible only in the region of the helium gyroresonance.

3. Turning to a discussion of radiation mechanisms, it should be noted that cyclotron instability of protons of the outer radiation belt cannot be responsible for the appearance of pearls for two reasons: a) the radiation spectrum of protons is broad; b) the proton belt is a comparatively stable formation, whereas series of pearls are an episodic phenomenon. The hydromagnetic radiation of protons of the outer radiation belt can be identified with the stationary noise in the range $\lesssim 1$ Hz observed at night (13). As for pearls, their appearance apparently indicates sporadic injection into the magnetosphere of fast protons, not yet detected by direct measurements on satellites. Under certain conditions, excitation of ion-cyclotron waves in the region of the helium gyroresonance is possible. The growth of the wave amplitude is limited by nonlinear losses in the exosphere with magnetic scattering of resonant protons.

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Note: Figure translations are in progress. See original paper for figures.